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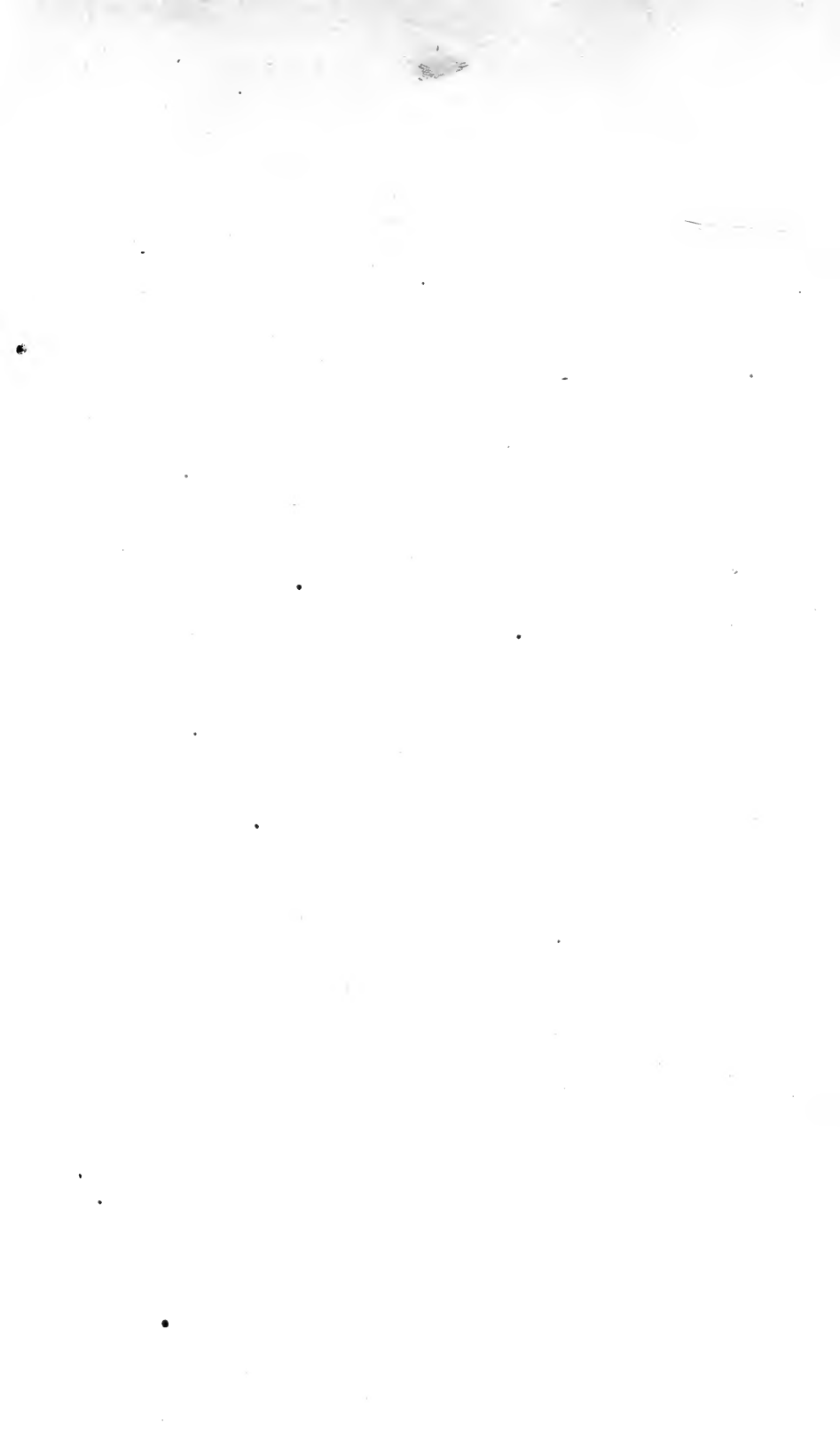
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HEAT

AS A SOURCE OF POWER;

WITH APPLICATIONS OF GENERAL PRINCIPLES

TO THE

CONSTRUCTION OF STEAM GENERATORS.

AN INTRODUCTION TO THE STUDY OF

HEAT-ENGINES.

BY

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PREFACE.

THE employment of heat as a source of energy, or power, is accomplished by a succession of processes which depend for their explanation on separate branches of applied science, and practically involve the use of different forms of apparatus, and the applications of different principles of mechanical construction.

The evolution of heat by combustion, its transfer to the bodies through which it acts, the changes which these bodies undergo when subjected to changes of heat, and the performance of work by expansion, through the medium of machines, mark successive steps which can be rationally and properly explained only by reference to the various sciences of chemistry, physics, dynamics, and mechanism, on which they respectively depend.

The most intricate and complicated of these processes are those which accompany the development of heat, and which depend on the relations of heat to chemistry, and to the physical constitution of bodies. A thorough knowledge of these relations, or laws, is of primary importance in all economical questions connected with the use of this agent as a source of power.

The dynamic theory of heat has furnished, through investigations which have been to a certain extent purely theoretical and mathematical, solutions of the principal problems connected with the work of expansion of gases and vapors; and these solutions, as well as those connected with mechanism, partake of the exactitude and certainty which belong to mathematical science. The principal laws connected with the development of heat, and the physical properties exhibited by bodies

under its varying influences, have, on the other hand, been discovered mainly through experimental researches, and the mathematical expressions of these laws are generally simple algebraic formulæ, which have been found to accord with the results of such investigations.

These elementary principles constitute the real basis of the science of heat, in its chemical as well as its dynamic relations, and a thorough comprehension of them is necessarily the first step to be taken in the study of heat-engines.

The *steam-engine* being the principal heat-engine in use at the present day, prominence must be given to the study of the *steam generator*, as the apparatus through which all processes preliminary to the actual use of steam are accomplished.

In an economical point of view, a thorough knowledge of proper forms of construction and of proper principles of management of this apparatus, is of no less importance than a knowledge of the laws of expansion, and of the mechanisms by which the heat of steam is utilized. There is, perhaps, even greater need of the dissemination of correct useful knowledge in regard to the construction and functions of the steam generator, than of the mechanism of engines, because the construction and use of the generator are more subject to the uncertainties of personal judgment and discretion; and ignorance of elementary principles in its use is more apt to cause waste.

The object of this work, as an introduction to the study of heat-engines, is simply to arrange and classify the elementary principles in such a way that they may be accessible to the student, unconnected with irrelevant matter; and in such forms as shall lead naturally to the succeeding steps—the study of the principles and mechanism of engines.

Any work of this character, on the subject of heat in any of its relations, must necessarily be a reproduction, to a great extent, of what in various forms has been published before; but the facts and principles which I have endeavored to arrange, are usually found scattered through text-books, in connection

with other subjects, and often without reference to technical applications.

I have endeavored to mention, as far as practicable, the various sources of information of which I have made use ; and desire to express my indebtedness to the authors of the works consulted.

SHEFFIELD SCIENTIFIC SCHOOL OF YALE COLLEGE,

January 8, 1874.



HEAT.

CHAPTER I.

HEAT.

1. **Dynamic Theory of Heat.**—The phenomena connected with *Heat* are so common and universal, so intimately related to the changes in constitution and form, of the elements which make up the material universe, and so essential to the existence of animal and vegetable life, as to render this one of the most important and varied in its influences of all the physical agents.

2. In its relation to animal and vegetable life, it may be said to be the main support of vitality; while, as a source of energy, it exists in all bodies as a *living force* in the literal or scientific, as well as the figurative, sense of this term.

3. The employment of this agent as a source of artificial power has given rise to investigations by scientific men during the last half century, which have become historical, and which have gradually led to the discovery of its true nature, or at least to a universally accepted theory regarding it; and it may be said, that while differences of opinion exist concerning the precise nature of molecular motions, the essential principles of the *Dynamic Theory of Heat* have become as well established as any other known or accepted law of physics.

4. In explaining this theory, heat has been defined to be a *mode of motion*; a definition which suggests appropriately the idea that it has its source in molecular motions of the atoms of substances in nature. But this definition, although of great value in aiding the popular comprehension, requires explanation, inasmuch as *motion*, or a particular kind of motion, as an abstract idea, does not involve the idea of force or energy.

5. It is not difficult to conceive of the existence of power, or

energy in connection with motion, however, if the motion be that of a mass or heavy body.

6. Actual energy, living force, vis viva, etc., are expressions employed by different writers to designate the capacity for performing work which is inherent in the motion of bodies, and which results from the velocity and mass combined; the measure of this capacity, or actual energy, being the mass multiplied by half the square of the velocity.

7. There is no principle of mechanics more universally recognized than this, and no law more commonly employed. In the ordinary movements of most animals its applications are so frequent and essential that it may be said to be a source of *economy* in muscular effort, while it performs a principal part in nearly all devices for the utilization of the various forces of nature.

8. The condition of a body, the particles of which are agitated by this peculiar heat-motion, is thus a condition of *energy*. The body has a certain amount of actual energy due to its mass and the resultant motion of its particles or molecules.

9. This energy may be expended, just as the energy of the fly-wheel may be expended, in overcoming resistances and *performing work*; or it may be increased by having the velocity of heat-motion increased, just as the energy of the fly-wheel is increased by energy stored up in an increased velocity.

10. In the case of the fly-wheel, an increase in velocity can be produced by the application of some external force, and a diminution of velocity, by the overcoming of some resistance, such as the raising of a weight, the compression of a fluid or spring, or the disintegration of some material.

11. In the first case the application of an external force develops motion in the mass of the fly-wheel, and the work of this force is thus transformed, or *converted*, into the *living force* or energy of the fly-wheel. In the second, living force disappears, with the diminution of motion, and is transformed or converted into external work.

12. The living force which constitutes the energy or power of heat, although not accompanied by the visible finite motion of the whole mass of a body in one direction, is nevertheless of the same nature and acts by the same law.

13. The exact nature of the heat-motion of the particles of substances has not been determined, and the ultimate arrange-

ment of these particles in the formation of bodies is still a matter of speculation.

14. There is, however, a universal acquiescence, on the part of scientific men, in the theory that the atoms or molecules of all substances have a vibratory or oscillating motion of a peculiar character, which may be called *heat-motion*.

15. The distance passed over by each atom at each vibration is inconceivably small, so small as to elude the senses, but the number of vibrations in an ordinary unit of time is, on the other hand, inconceivably *great*.

All substances possess this heat-motion. The absence of it in nature cannot be conceived without carrying with this conception the idea of the destruction of animal life, and a complete change in the elements as they are now presented to us.

So that under this view, all solids, liquids, and gases, as far as now known, being animated by this peculiar motion, heat may be regarded as a *property of matter*.

According to the dynamic theory, a change in the heat of a body implies simply a change in the velocity of vibration of the particles, and the particles having weight or mass, a change of heat involves the development or disappearance of living force.

16. The various phenomena connected with heat may be divided into three classes :

1. *The action of the heat of a body as a source of power or energy in performing work external to the body in which it exists, and internally in changing the relative positions of the particles, or producing expansions and contractions of volume ; and, conversely, the generation of heat in a body accompanied by change of volume and density by the application of external work.*

2. *The changes which bodies undergo in form and other properties when subjected to changes of heat.*

3. *The transfer of heat from one body to another.*

17. A consideration of the third class of phenomena, the transfer of heat, involves the introduction of an element in the material world, the existence of which cannot be made evident to the senses in any ordinary manner, but which is proved by analogy and scientific reasoning.

18. While the molecules or atoms of substances are aggregated in the closest proximity and have incessant motion, there is presumed to be a gaseous or ethereal substance pervading all

space, the particles of which are so small, compared with ordinary material atoms, that the ether permeates the spaces between the atoms of substances, and is capable of being set in motion or vibration by the motions of these atoms.

19. On the other hand, motion communicated to this ethereal medium at a point external to a body, and transmitted in the form of waves, may, through the action or impact of these waves with the particles of a body, impart motion to them.

20. Popular attention is often directed to these *wave-motions* as the source and cause of heat and light. But the view most generally accepted appears to be that which places the source of energy in the incessant motion of the molecules of substances, and regards the ethereal substance as a medium of transfer, just as the atmosphere is, in an analogous manner, the medium of transfer of the vibrations of bodies in the production of sound.

21. The *radiation* of heat is then but a wave-motion communicated to the ethereal medium by the action of the atoms or molecules of bodies. A heated body loses heat-motion, and living force, in sending off waves in this medium; and another body, in the path of these waves, will have the motions of its molecules increased in velocity and will become heated. The particles of the ethereal medium, having weight or mass, possess energy when in motion and impart this energy to the material atoms.

Thus arise the phenomena of *radiant* heat and light; phenomena which, when studied and observed in reference to the wave-motions alone, present all those interesting effects of heat and light which arise from different lengths and velocities of the waves—interference, polarization, diffraction and reflection—giving rise to different colors, as well as different heating effects, from the same source of motion.

22. These phenomena belong to the general subject of physics, and may be omitted in the discussion of heat as a source of energy. It is to be remarked, however, that one of the unsettled questions in the views of scientific men on this subject, is, whether the origin of heat-motion in matter lies in the motion of the particles of the ethereal medium, or solely in the motion of the atoms of bodies, or in both combined.

23. The view generally accepted is that stated above, the origin of force being supposed to exist in the motions of the atoms, or molecules.

24. Under this view the first and second classes of phenomena become intelligible, and may be subjected to rigorous analysis as well as rational explanation. Every body—by which is to be understood a *definite quantity by weight or volume* of a given substance—is supposed to be composed of heavy atoms, each of which is in incessant motion, though the velocities of oscillation of all the particles may not be identical. There results, however, a certain mean or average velocity of motion, and the living force of the whole body due to the heat-motion of all the particles may be expressed by the well-known law of the mass multiplied by one-half the square of the mean velocity.

25. By algebraic symbols, if v represent the mean velocity of the heat-motion in a body the mass of which is M , the actual energy due to this heat-motion will be

$$\frac{M \cdot v^2}{2}$$

and if v_1 represent any other velocity, the actual energy corresponding to this velocity will be

$$\frac{M \cdot v_1^2}{2}$$

and the difference $M\left(\frac{v^2 - v_1^2}{2}\right)$ will represent the expenditure of energy, or the *work of inertia*, due to the change.

If there is a loss of heat, or a loss of velocity, energy will be expended, and if a gain of heat, energy will be stored.

26. Heat as a source of energy may therefore be regarded simply as the work of the *force of inertia*. * As the fly-wheel possesses power derived from its mass and rapid motion to drive machinery, so all substances possess energy, derived from the rapid oscillation of the individual molecules, to perform work, when these oscillations are diminished. The rapid oscillations of the particles of steam, or gas, constitute the source of power in heat-engines. These particles, enclosed by a cylinder one end of which is movable, strike the movable end, or piston, and give it motion; the effect on the heat-motion of the particles of steam, or gas, being to diminish the living force of the whole mass of steam enclosed by a quantity which is identical with the work performed by the piston.

27. It is, then, the force of inertia which drives mills, steamships, and factories, under the name of heat, and which

+ Hardly proper to designate it "force."

has become, in a new and unexpected manner, a universal aid to man.

28. The STEAM-BOILER is the apparatus by which, through the process of combustion, a rapid degree of heat-motion is developed in the fuel and gaseous products of combustion, and transferred to the particles of water; the *steam-engine* is the apparatus in which the heat-motion is again partially destroyed, the inertia developed by this change being the force which performs the work of the machine.

29. When work is thus performed, there is necessarily an exact equivalence between the cause and effect. In ordinary mechanics it is well known that the expression

$$M\left(\frac{v^2 - v_1^2}{2}\right) = P \times h$$

rationally interpreted, denotes that the work performed by the inertia of the mass M , when its velocity is changed from v to v_1 is equivalent to the work estimated by multiplying a force P by a distance h ; to find the value of the product $P \times h$, it is only necessary to give numerical values to the quantities M , v , and v_1 . M is equal to $\frac{W}{g}$, the weight divided by the numerical expression for the force of gravity; v and v_1 are usually determined by observation, and are expressed in feet per second.

30. When this expression represents the work performed by the inertia for a given change of heat-motion, a difficulty presents itself in an attempt to give numerical values to the quantities.

The mass may be found as before, being the weight of the body divided by the force of gravity, numerically expressed; but the velocities v and v_1 belong to motions which elude the senses.

The second member of the equation, $P \times h$, may, however, be expressed in the same numerical terms as before, a pressure or weight multiplied by the distance or space through which it acts. It is obvious that where the whole effect of a change of heat is the performance of a certain work, $P \times h$, if the external work can be measured the *numerical value* of the *first member* may be determined.

31. Experiments of this character have been performed, and those of Mr. Joule, from having been the first thorough and systematic experiments made with this object, have caused his name to be connected most prominently with such researches.

His experiments were made with an apparatus consisting of a small cylindrical case filled with water, in which blades were made to revolve, by the application of power furnished by a weight attached to a cord which passed over a fixed pulley. The water in the case was prevented from rotating in a vortex with the blades, so that the only effect of the motion of the blades was to produce friction among the particles of water. This friction developed heat in the water; and the work exerted to drive the blades, viz., a weight falling through a height, was measured.

32. A numerical expression for the *work* was thus easily found.

In mechanics, it is well known that a unit of work is composed of two other units, a unit of weight and a unit of distance—in English measures one pound, and one foot; so that one pound raised one foot high is called a unit of work, or a *foot-pound*.

33. The question then occurs, how shall the change of heat which a given amount of work produces, be measured? There must necessarily be some *unit* for such measurement; and since the velocities of the particles cannot be observed, recourse is had to an arbitrary unit of heat.

34. It might be presumed that if a body be exposed continuously to the same cooling influences for a certain length of time, the effects would be equal in equal times; or if a body be exposed continuously to the same influence which increases the velocity of heat-motion, or the same heating influences, the effects of these influences would be equal in equal times; popularly speaking, the quantity of heat which would leave or enter the body in equal times would be equal. So that if we always had the same source of heating or cooling, this quantity of heat might be measured by the *time*, and a heat-unit based on time might be employed.

35. If we were to represent by 1 the *quantity of heat* lost or gained in one unit of time, we could represent by 1 multiplied by a number of seconds any other quantity of heat, and the expression

$$M\left(\frac{v_2^2 - v_1^2}{2}\right)$$

would be represented in terms of this unit, and it would only remain to determine experimentally how many units of work correspond to one unit of heat, or the value of $r \times h$ for one unit of heat.

36. But we have not always the same constant source of heating or cooling. On the contrary, heat-motion is developed or destroyed by a great variety of physical agencies, such as chemical composition, decomposition, electricity, radiation, and conduction. Some other arbitrary unit must therefore be found, and advantage is taken of the property which all substances possess, of changing form when heated or cooled, independently of the source of heating or cooling.

37. It is known, from observation and experience, that substances generally expand when heated and contract in volume when cooled, and it is further known that these phenomena are independent of the nature of the source which causes the changes, so that generally, in solids, liquids, and gases, a given change of heat is accompanied by a corresponding change in the volume of the body heated or cooled, whatever may have been the source of heating or cooling.

38. This law is so invariable that the amount of expansion of a body may be taken to indicate changes of heat.

39. The construction of the common thermometer is based on this idea. The thermometer, when applied to a body, indicates the degree or velocity of heat-motion of the molecules, the heat-motion being more or less rapid according to the expansion of the fluid of the thermometer as indicated by its scale.

40. We thus have what are known as degrees of heat or degrees of *temperature*, the term *temperature* indicating a *condition* of the body merely, and changing in a manner proportional to the change of heat—the term temperature in this respect being somewhat analogous to the term velocity, in treating of ordinary motions of heavy bodies. And because the thermometer is brought into a condition of heat in equilibrium with that of the body to which it is applied, by mere proximity, or contact, it may be said to indicate the *sensible* heat of the body, or power of the body to communicate heat to other bodies.

41. If now we take a pound of water, and cause a change of heat indicated by a change of *temperature* of *one degree* of the thermometer, we have all the elements necessary for a heat-unit.

The mass or weight is known, and we have found a measurable quantity—the volume of the mercury or other substance employed as a thermometer—which changes with the changes of

heat, or as $\frac{M v^2}{2}$ changes.

42. We may now assume *the change of heat corresponding to one pound of water raised in temperature one degree to be one UNIT OF HEAT.*

For water, the quantity of heat, measured by *heat-units*, corresponding to any change of heat, may then be represented by the number of pounds of water multiplied by the number of degrees of the thermometer which indicates the change of temperature.

43. It was found by Joule, in the experiments referred to, that one unit of heat corresponds, or is equivalent to, 772 foot-pounds of work, water being taken at a temperature of 39.1° Fahrenheit, its point of maximum density. This experimental determination has been abundantly verified by other experiments made by different philosophers, in various modes, so that 772 foot-pounds is now known as the *dynamic equivalent* of a unit of heat in English measures. In French measures the unit of heat is called the Calorie, and is the quantity of heat which corresponds to a change of heat indicated by one degree of the centigrade thermometer, in one kilogram (2.20 lbs.) of water, the water being taken at its maximum density. This unit is equivalent in French measures to 423.55 kilogrammetres, or 423.55 kilograms raised one metre.

44. The fundamental law of *Thermodynamics*, or of the dynamic theory of heat, is involved in what has already been stated.

Heat and mechanical energy are mutually convertible, the conversion being the transformation of living force into work, or the reverse; one unit of heat being equivalent to 772 foot-pounds.

The rational interpretation of the term *unit of heat* employed in this enunciation, is that the *work of inertia of the particles of water, or the change of living force, which occurs when the heat of one pound of water is changed by a quantity represented by 1° Fahrenheit, is equivalent to 772 foot-pounds.*

45. In the application of mathematics to the subject of heat this is called a quantity of heat represented by unity. A quantity of heat represented by any number would be this quantity repeated as many times as there are units in the number.

If W represent any quantity of work in foot-pounds, $\frac{W}{772}$ will represent the equivalent quantity of heat expressed in *heat-units*, one expression representing the effect and the other the

cause; or, Q , expressed in heat-units, multiplied by 772, will give the number of foot-pounds equivalent to a given quantity of heat.

46. Passing to other substances, it may be stated that the *heat-unit* of any substance is that quantity of heat which corresponds to a change of 1° in the temperature of 1 pound of the substance.

47. The heat-units, or *specific heats* of different bodies, are all different, as the name implies; and as it is convenient to have but one *unit of heat*, that of water is chosen as this unit, and the specific heats of other substances are expressed relatively to that of water.

48. Tables giving the specific heats of substances, so expressed, may be found in nearly all standard works which treat of heat. A very complete set of such tables is given in Watts's Chemistry. It is to be observed, in regard to specific heats, that all known substances, except hydrogen, require less heat for a change of temperature of one pound of the substance one degree than that which is required for water.

49. This is an accidental property of water, but the result is, that in a table of specific heats the numbers which represent the specific heats are, with the exception of that for hydrogen, less than unity.

50. To find the quantity of heat corresponding to any given change of temperature, in a given quantity of any substance, requires, then, three factors—the *number of pounds*, the *change of temperature in degrees*, and the *specific heat*.

This last factor for water (at 39.1° , or maximum density) being unity, and for other substances, the specific heats may be found from the tables. A quantity of heat represented by Q , that is, a change of heat equivalent to Q expressed in heat-units, may be expressed by symbols thus:

$$Q = W \times C \times F$$

w being the weight of the body, c the specific heat, F the number of degrees of change of temperature.

51. It is evident that if three of the above quantities are the known quantities in any problem, the fourth can be determined.

52. The following tables, taken from Watts's Chemistry, exhibit the mean specific heats of the substances named:

TABLE I.

SOLIDS.	Specific Heat.
Copper.....	0.0951
Gold.....	0.0324
Iron.....	0.1138
Lead.....	0.0314
Platinum.....	0.0324
Silver.....	0.0570
Tin.....	0.0562
Zinc.....	0.0955
Brass.....	0.0939
Glass.....	0.1977
Ice.....	0.5040
Sulphur.....	0.2020
Charcoal.....	0.2410
Alumina.....	0.1970
Stones, Bricks, etc., about.....	0.2200

LIQUIDS.

Water.....	1.0000
Lead (melted).....	0.0402
Sulphur “.....	0.2340
Bismuth “.....	0.0363
Tin “.....	0.0637
Mercury.....	0.0332
Alcohol.....	0.6150
Fusel Oil.....	0.5640
Benzine.....	0.4500
Ether.....	0.5034

GASES.

	At constant pressure.	At constant volume.
Air.....	0.238	0.169
Oxygen.....	0.218	0.156
Hydrogen.....	3.405	2.410
Steam-Gas.....	0.480	0.346
Carbonic Acid.....	0.217	....
Nitrogen.....	0.244	....
Olefiant Gas.....	0.404	0.173
Carbonic Oxide.....	0.245	0.237
Ammonia.....	0.508	0.299

53. The above specific heats are average values, taken at temperatures which usually come under observation in technical applications. The actual specific heats of all substances in the solid or liquid states increase slowly as the body expands, or as the temperature rises, and when *great accuracy is required* tables of specific heats may be consulted which will give these quantities with greater definiteness at special temperatures.

54. The following examples will illustrate the use of the tables in solving problems relating to changes of heat and changes of temperature.

Example 1.

Let it be required to ascertain what rise of temperature Fahr. will result from the transfer of 1,000 units of heat by any process whatever, such as radiation or friction, to 100 lbs. of iron taken at any ordinary temperature.

In the expression

$$Q = W \times c \times F$$

$Q = 1,000$ units of heat,

$c = 0.1138$ specific heat of iron from tables,

$w = 100 =$ weight of iron as enunciated,

F the unknown quantity to be determined, we have

$$F = \frac{Q}{w \times c} = \frac{1,000}{11.38} = 87^{\circ}.87$$

55. The specific heats of gases are given for constant pressure and for constant volume. It is well known that a gaseous substance, to be treated as a quantity or body having volume, must be confined by some envelope or within an enclosure through the sides of which the gas cannot escape. Such an enclosure may have an invariable volume, that is, its sides may not yield to any pressure from the interior, or it may have a variable volume, as when air is enclosed in an elastic envelope or within a cylinder having one end movable. The effect of transferring an additional quantity of heat to a given weight of gas, is to cause it to expand in volume if the envelope will admit of expansion.

If the envelope expands sufficiently to adjust the new volume to the external pressure, this external pressure being constant, the specific heats to be employed in determining quantities of heat are those given under the head *constant pressure*.

If the volume remain invariable, the specific heats to be used are those under the head *constant volume*.

Example 2.

56. Let 1 lb. of air be enclosed in a vessel of invariable volume, and let it be required to find the *number of units of heat* to be transferred to or from this quantity of air to cause a change of temperature of 50° Fahr.: we will have

$$Q = W \times C \times F$$

where $w = 1$ lb.

$c =$ specific heat of air at constant volume.

$F = 50^\circ$.

$Q = 1 \times 0.169 \times 50^\circ = 8.45$ units of heat.

If this air be allowed to expand while being heated under a *constant pressure*, the quantity of heat required would be

$$Q_1 = 1 \times 50 \times .238 = 11.9 \text{ units of heat,}$$

and the equivalent in work would be

$$Q_1 \times 772 = 11.9 \times 772 = 9186.8 \text{ foot-pounds. } +$$

In this case the air is not only heated to the same degree as before, but it expands by a certain quantity, and the work of expansion against a constant pressure requires an additional quantity of heat.

57. Action of Heat upon Bodies in Nature.—The general theory of heat having been considered, we are led in the next place to examine the effect which a change in heat-condition produces in bodies in nature.

With this end in view it is desirable, first, to classify bodies according to the forms and properties which they assume or exhibit as they are ordinarily presented to our senses, viz.: Solids, Liquids, Gases.

58. Solids.—A solid body is a body the molecules of which, though in a state of incessant vibration, nevertheless are retained in such a state of equilibrium between the attraction of the molecules for each other and the oscillations due to heat, that the body, as a whole, retains the state which is called solid. The conditions of equilibrium of the molecules, when there is no change in the heat of the body, can only be altered by external forces.

59. Liquids.—In the liquid state the molecules of the body

$$+ \text{Work} = (Q_1 - Q_2) \times 772$$

move freely among themselves, but are not permanently attached to each other. In other words, a single molecule may transfer its contact from one set of molecules to another set, subject to the condition that the particles or aggregated molecules remain in mutual contact like so many minute spheres or globules, rolling freely upon each other, but still retained in mass by the attractive forces which act through their point of contact.

60. **Gases.**—In the gaseous state the molecules are removed entirely beyond the spheres of their mutual attractions. When the molecules of a gas meet they repel each other, and thus a gas will expand indefinitely if it be not enclosed within an envelope.

Nearly all substances in nature, as far as known at present, are capable of assuming all of the above states under certain conditions of heat; the action of heat upon a solid being first to cause expansion or increase of volume, then fusion or melting, a change from the solid to the liquid state, and as the heat of the body increases, a further change from the liquid to the gaseous condition.

Some gases, however, known as *permanent gases*, viz., air, oxygen, nitrogen, nitric oxide, carbonic oxide, and marsh-gas, have never been obtained in the liquid state.

61. A definite quantity of any given substance requires three conditions for its existence in a separate and distinct form; these are *volume*, *pressure*, and *temperature*.

By volume is to be understood the actual space occupied by the substance without regard to the form of that space; by pressure, the resistance of the external envelope of the body to its expansion; and by temperature, the condition of heat-motion of its particles.

The effect of a change of heat must therefore be the same for all.

62. The transfer of heat to a solid not only causes an increase of molecular vibration, which is exhibited by an increase of temperature, but an expansion, which consists in the separation of the particles from each other, or an increase of volume; but this expansion involves the overcoming of the external pressure of the air or other enveloping medium.

63. In the case of liquids, a transfer of heat to the liquid produces precisely the same effects as in the case of a solid; increase of molecular vibration, disintegration, involving expansion of volume, and overcoming of the external pressure.

64. In the case of perfect gases, the molecules having already become entirely separated, the effect of a transfer of heat to a gas is exhibited simply in increase of vibration of the particles, or increase of sensible heat (temperature), and the overcoming of the external pressure.

65. When heat is abstracted from a body, the effects described above are all reversed. The molecular oscillation is diminished, the volume contracts, and the external pressure, acting through the volume passed over by the contracting envelope, will perform work which appears in the heat abstracted.

66. These general laws may be illustrated or explained in a very simple manner, according to the fundamental theory of heat which has been enunciated, by the use of algebraic symbols.

Suppose a definite quantity of any body, solid, liquid, or gaseous, to receive heat from some external source. Let the quantity of heat received, expressed in units of heat, be denoted by q . The body will undergo the following changes :

1st. An increase of molecular movement involving an increase of actual energy or living force, which may be represented by A .

2d. A certain amount of expansion or change of position of the particles, which involves a certain amount of work in overcoming the attractive forces of the body, which may be represented by B .

3d. The change of volume involves the work of overcoming the external pressure to an amount which may be represented by C ; and since q is expressed in units of heat, and A , B , and C are supposed to be expressed in units of work—foot-pounds—we shall have, for the total effect of the heat transferred,

$$q = \frac{A + B + C}{772}$$

In solids and liquids, the expansion being small in comparison with the original volume, C will be very small, and may be left out of consideration, and the expression will become

$$q = \frac{A + B}{772}$$

In perfect gases, the forces of attraction of the molecules having been entirely overcome, the quantity B will disappear, and we shall have

$$q = \frac{A + C}{772}$$

This is the most important case in technical applications, because the employment of heat as a source of power is usually through the medium of gases, and this expression shows that the only effects of a change of heat are a change in the molecular vibrations of the gas, involving living force, and the overcoming of external pressures.

If heat be abstracted, the effects are similar but reversed; the external pressure acts in the same direction, and the oscillations of the particles or molecules are diminished.

67. In the case of bodies which are known by observation to contract when heated, at certain temperatures, or to expand when cooled, as water and some alloys, the sign of the term c will be reversed at these points, and the expression will furnish an explanation of the peculiar phenomenon, that under these circumstances an increase of external pressure will lower the temperature of fusion or congelation—a fact announced by Prof. James Thomson, and afterwards verified by experiment by Prof. Wm. Thomson.

68. The above laws are general; and bodies which expand when heated under constant pressure, usually regain their original volume when cooled to their original temperature.

There are, however, some remarkable exceptions. It is well known that water has a point of maximum density, or a point at which the volume of a given quantity is the least. This temperature is 39.1° Fahr. If water be cooled below that temperature, it expands, and if heated from a point below that temperature, it contracts until that temperature is reached.

Another exception is Rose's fusible metal. There is a certain temperature of maximum expansion beyond which, if it be heated, it contracts. Another remarkable exception is given by Balfour Stewart, as results of experiments by Fizeau, which show that iodide of silver contracts by heat and expands by cold at any point between the temperatures 10° and 70° Centigrade.

Moreover, the enunciation of the law that bodies when heated and then cooled to the original temperature, regain their original volume, requires a further condition in the case of most solids. The cooling must be slow and gradual. If abrupt and sudden, the original volume may not be regained, and peculiar effects are often produced which are difficult of explanation, such as brittleness and hardness.

The process of annealing, or slow cooling, is essential when certain conditions in these respects are desired.

Assuming as the general law that bodies expand when heated, and that nearly all bodies may be made to assume the three conditions described as solid, liquid, and gaseous, we may examine the phenomena which occur when any substance passes under the influence of heat, from the solid to the liquid and gaseous conditions.

69. Coefficient of Expansion.—The rate of expansion of a body is the increase of volume which takes place for equal increments of temperature, the volumes being referred in each case to the volume of the same body at a standard temperature.

When a body exists in the form of a rod or bar, the length of which is to be determined under different degrees of heat, the increase of length is called the linear expansion.

This is evidently not a measure of the total increase of volume, but it is convenient in practice to know the linear expansion as well as the cubical expansion.

70. The following table gives the numbers by which it is necessary to multiply the lengths of rods or bars at 32° Fahrenheit in order to find the lengths of the same rods or bars at 212° Fahr. In other words, the numbers show the increase of lengths of rods of the same substance for 180° Fahr. (from 32° Fahr.). The proportional expansion for 1° Fahr. may be found by dividing each number by 180.

II. *Table of Linear Expansions of Solids.*

NAME OF SUBSTANCE.	Length at 212° Fahr. of a bar or rod the length of which at 32° is 1.00000 (unity).	OBSERVER.
Glass tube.....	1.00082	
Plate-glass.....	1.00089	Lavoisier & Laplace.
Crown-glass.....	1.00088	“ “
Cast-iron.....	1.00111	“ “
Steel-rod.....	1.00114	Roy.
Steel, tempered yellow.....	1.00136	Lavoisier & Laplace.
Steel, tempered at light heat	1.00123	“ “
Steel not tempered.....	1.00107	“ “
Soft iron, forged.....	1.00122	“ “
“ drawn.....	1.00123	“ “
Iron wire.....	1.00144	Troughton.
Bismuth.....	1.00139	Smeaton.

Gold, unannealed.....	1.00155	Lavoisier & Laplace.
“ annealed.....	1.00151	“ “
Copper.....	1.00172	“ “
Cast brass.....	1.00187	Smeaton.
Brass wire.....	1.00193	“
Silver.....	1.00191	Lavoisier & Laplace.
Spelter solder.....	1.00205	
Tin.....	1.00284	Muschenbrock.
Zinc.....	1.00296	Smeaton.
Lead.....	1.00284	“

The above table is taken from a more comprehensive table in Watts's Dictionary of Chemistry, to which the reader is referred for more complete information.

A complete table of cubical expansion for various solids is given also in the same work ; such a table is omitted here, because for most practical purposes the cubical expansion or coefficient of expansion of volume for any substance may be obtained by multiplying the linear expansion given in the above table by 3. The coefficients of linear and cubical expansion thus found are average values for degrees of heat between 32° and 212°, but these coefficients become slightly greater at higher temperatures ; the general rule being that the coefficient of expansion increases the more rapidly as the temperature approaches that which corresponds to the melting or fusing point.

71. Liquefaction, Melting, or Fusion.—The continuous transfer of heat to a solid, causing a continuous rise of temperature and expansion of volume, produces ultimately a change of aggregation or change of state to the liquid form, called the fusion, melting, or liquefaction of the substance.

This law is general for substances which do not change their composition in changing their state. For substances which do not change their composition the following phenomena occur :

1. “ Each substance begins to melt at a certain temperature, which is constant for the same substance if the pressure be constant.”

2. “ The temperature of the solid remains at this constant point from the time when fusion commences till it is complete.”

3. “ If a substance expands in congelation, its melting-point is lowered by pressure ; but if a substance contracts in congel-

ing, its melting-point (or point of congelation) is raised by pressure." *

72. The following table of melting-points in Fahr. degrees is taken from Rankine's Rules and Tables:

III.

Mercury.....	-38°	Fahr.
Ice.....	32°	"
Rose's fusible metal....	210°	"
(1 part lead, 1 tin, 2 parts bismuth.)		
Sulphur.....	228°	"
Tin.....	426°	"
Bismuth.....	493°	"
Lead.....	630°	"
Zinc.....	700°	"
Silver.....	1280°?	"
Brass.....	1869°?	"
Copper.....	2548°?	"
Gold.....	2590°?	"
Cast-iron.....	3479°	"
Wrought-iron.....	—	higher, but uncertain.
Phosphorus.....	111°	"
Wax.....	147°	"

The temperature at which this change of state occurs is, for most substances, a *fixed temperature*; this temperature indicating the limiting condition above which the substance exists as a liquid, and below which it must exist as a solid.

73. The laws which have been enunciated are subject to certain qualifications, such as slow process of cooling, and variations of external pressure, which may lower the temperature of solidification, but under the same conditions they are invariable.

The continuous application of heat to a solid at its melting-point does not raise its temperature, as long as any portion remains solid; and, commonly, the abstraction of heat from a liquid at its point of solidification, does not lower its temperature, as long as any portion remains liquid.

The change of state is also usually accompanied by a sudden change of volume.

Some substances, however, pass from the solid to the liquid state without showing a definite melting-point, becoming plastic

* Balfour Stewart: Elementary Treatise on Heat, p. 87.

between these states. Glass and iron are examples, and instead of a definite melting-point, a certain interval of temperature is required for the change.

74. Changes of Volume in Melting.—When bodies pass from the solid to the liquid state, the increased rate of expansion is generally followed by a further expansion, so that the substance, after fusion, occupies a greater bulk at the same temperature than before fusion.

Phosphorus expands at the moment of fusion about 3.4 per cent., sulphur 5 per cent., wax very slightly, stearine about 5 per cent.

Rose's fusible metal exhibits remarkable properties in this respect. It is composed of 2 parts of bismuth, 1 of lead, and 1 of tin. When heated from 32° Fahr. to about 108°, it expands in the ratio of 1 to 1.0027; as the temperature is further increased, it contracts, its volume at 190° Fahr. being the same as at 32°. In melting it expands again, so that at 208° its volume is 1.01 of its volume at 32°. This alloy, therefore, contracts from 108° to its melting-point (Watts's Chemistry).

Water, as is well known, expands at the moment of fusion, or contracts in melting about 10 per cent.; one volume of water at 32° Fahr. gives 1.102 volumes of ice, and one volume of ice .908 volume of water at the same temperature. Bismuth, cast-iron, and antimony expand like water in passing from the liquid to the solid state.

75. Latent Heat of Fluidity.—The increase of the specific heat of a solid, as it approaches its melting-point, appears to be connected with the increase of the coefficient of expansion, which also increases simultaneously. At the melting-point the whole of the heat applied to a body is apparently required to overcome those molecular attractions which keep the molecules in the state of proximity belonging to the solid condition. The *work* of the heat applied is thus absorbed or expended without producing increased molecular vibrations.

Heat which would have become sensible heat in the pure solid or liquid, disappears or is transformed into the work of overcoming these molecular attractions, and is said to become *Latent*.

The latent heats of fusion of a few substances, estimated in units of heat, have been determined experimentally by various observers, and some of these quantities are exhibited in the following table:

IV. *Latent Heats of Fusion of different Substances, according to Person.*

Mercury.....	5.086	British unit of heat.
Phosphorus.....	9.018	“ “
Lead.....	9.740	“ “
Sulphur.....	16.954	“ “
Bismuth.....	22.726	“ “
Tin.....	25.702	“ “
Silver.....	38.057	“ “
Zinc.....	50.682	“ “
Ice.....	140.000	“ “
	144.000	

76. **Liquids.**—The coefficient of expansion of liquids with increase of temperature is greater than that of solids, and, as in the case of solids, the coefficient increases with the temperature.

The coefficient of expansion of mercury (*i.e.*, the increase of volume for 1° C. in terms of the volume at 0° , or the melting-point of ice) increases from 0.000179 at 0° C. to .000197 at 350° C.

The following table gives the increase in volume of water from the experiments of Kopp, taken from Balfour Stewart :

V. *Expansion of Water from 0° Centigrade to 100° .*

4°	1.000000
10°	1.000247
15°	1.000818
20°	1.001690
30°	1.004187
40°	1.007654
50°	1.011890
60°	1.016715
70°	1.022371
80°	1.028707
90°	1.035524
100°	1.043114

When cooled below 4° Cent. (39.1 Fahr.), water expands by a corresponding and nearly identical law for a limited number of degrees.

In regard to very volatile liquids, like carbonic acid, which retains its liquid state at ordinary temperatures, only under

very great pressure, the coefficient of expansion is supposed to be large relatively. Tables of expansion for various liquids may be found in the excellent work of Balfour Stewart, to which reference has already frequently been made.

The tables referred to show that each liquid has a coefficient of expansion different from that of other liquids. To this fact may be added the general law, that the coefficient of expansion of the same liquid varies with the temperature according to a special law for each fluid.

77. It may be observed, from the tables of coefficients of expansion for solids and liquids, that the total change of volume from the lowest to the highest temperature consistent with the solid or liquid condition of any substance, is very small compared with the actual volume of the body which undergoes such a change, and hence the influence of the external pressure upon the bounding surfaces is very slight during the change. In other words, the work performed by heat in expanding liquids and solids may be regarded as entirely expended in producing change of temperature and change of aggregation, the external work in all ordinary cases, especially when the solid or liquid is exposed only to atmospheric pressure, being so small that it may be disregarded.

In the case of bodies in the gaseous condition, however, this is different. Gaseous bodies cannot exist in a fixed or determinate volume, ordinarily, unless they are enclosed within bounding surfaces or envelopes.

The force of cohesion among the particles of a gas no longer exists as in the solid and liquid states, and the heat-condition of a perfect gas consists simply in the oscillation of the molecules, (which is represented by the actual *temperature* of the gas,) and the outward pressure or repellent action of these molecules which must be resisted by the envelope.

For a definite volume of a gas thus confined, there are thus but two conditions involved in its existence: the temperature and the pressure which it exerts against the bounding surfaces of the envelope.

If such an envelope be perfectly elastic and heat be transferred to the gas (the external pressure, such as the pressure of the atmosphere, remaining constant), the effect will be an expansion of volume. This expansion will be much greater than the expansion of liquids and solids for the same increase of heat.

The coefficient of expansion or increase of *volume* under such circumstances, for an increase of temperature of 1° Fahr., has been determined, through the well-known experiments of Regnault and others, to be 0.002035 or $\frac{1}{491.4}$ of the volume of the gas at 32° Fahr., and for 1° Centigrade, 0.00365 or $\frac{1}{273}$ of the volume of the gas at 0° C.

If we now compare the cubical dilatation of solids, liquids, and gases in a general way, we may take for such comparison the increase of volume from 0° to 100° Centigrade.

78. The following table is taken from Rankine's Rules and Tables:

VI. *Expansion for 100° Centigrade.*

Gases.....	0.365	Wrought-iron and steel.	0.0036
<i>Liquids.</i>		Lead.....	0.0057
Pure water.....	0.04775	Tin.....	0.0066
Sea-water.....	0.05	Zinc.....	0.0058
Spirit of wine.....	0.1112	Brick, common.....	0.0106
Mercury.....	0.0182	Fire-brick.....	0.0015
Oil, linseed and olive.	0.08	Cement.....	0.0042
<i>Solids.</i>		Glass.....	0.0027
Brass.....	0.0065	Slate.....	0.0031
Bronze.....	0.0054	<i>Average Values.</i>	
Copper.....	0.0055	Solids.....	0.005
Cast-iron.....	0.0033	Liquids.....	0.060

The numbers under the head Average Values exhibit in a general way the relative average expansion in bulk of solids and liquids, between 0° and 100° C. or 32° and 212° Fahr.

The expansion of gases, 0.365, is strictly true only for the perfect gases, *i.e.*, gases which have not been liquefied.

In the above comparison of the changes of volume of solids, liquids, and gases under equal changes of heat, the coefficients for solids and liquids are only mean values between 0° and 100° Centigrade.

And, moreover, as before remarked, each *solid* or *liquid* substance has its own coefficient, which increases slightly as the tem-

perature rises. In regard to gases, however, a more simple law holds true. The coefficient .00365 for each degree Centigrade, or .0020276 for Fahr., is the same for all perfect gases and for all pressures upon the external envelope; provided only that the pressure be constant during the change of volume or during the transfer of heat.

Thus one volume of a perfect gas at 0° Cent. or 32° Fahr. will become $1 + .00365$ or $1\frac{1}{273}$ volume at 1° Centigrade or $1 + 0.002035$ or $1\frac{1}{491.4}$ volume at $32^{\circ} + 1^{\circ}$ Fahr.

A slight difference in the coefficients was found by Regnault for the different gases, and also a slight difference at different external pressures; but for purposes of ordinary calculation the coefficients of all *perfect gases* may be regarded as the same.

79. We may conceive, however, that when heat is transferred to a gas enclosed within an envelope (for instance, within a cylinder which is closed at one end by a movable piston), the *volume* and the *external pressure* may change simultaneously, and thus the three quantities which determine the condition of the gas, viz., the volume v , the pressure p , and the temperature t , may all be variable quantities.

The relation between these quantities, under such conditions, has been found, and is represented by what is well known as the law of Mariotte and Gay-Lussac. The following simple equation is the mathematical enunciation of this law:

$$p v = R (a + t)$$

in which p is the external pressure upon unit of surface, v the volume of unit of weight, R a constant which depends on the specific gravity or density of the gas (the weight of this unit of volume), t the temperature, and a the number 273, Centigrade degrees being employed, and 459.4 if Fahr. degrees be employed.

The quantity p , defined as the external pressure upon a unit of surface, is evidently also the outward pressure of the gas. In the illustration in which the gas is supposed to be confined in a cylinder with a movable piston, it is apparent that when there is a state of equilibrium, the external and internal pressures must be equal. Hence the pressure p is also called with propriety the *elastic force* of the gas, which is always exerted in an outward direction.

80. Mariotte's and Gay-Lussac's laws * combined are expressed by the following formulas:

$$\frac{PV}{273+t} = \frac{P_0 V_0}{273+t_0} \quad (\text{for Centigrade degrees})$$

or

$$\frac{PV}{459.4+t} = \frac{P_0 V_0}{459.4+t_0} \quad (\text{for Fahrenheit degrees})$$

In this expression P represents the pressure in pounds upon one square foot, and v the volume in cubic feet occupied by one pound of the gas at any temperature t (either Cent. or Fahr.), $P_0 V_0$, and t_0 represent respectively the pressure, volume, and temperature of the gas at 0° Cent. or 32° Fahr.

When absolute temperatures are employed this formula may also be written as follows:

$$\frac{PV}{T} = \frac{P_0 V_0}{T_0}; \text{ hence } PV = \frac{P_0 V_0}{T_0} \times T$$

If D_0 represents the density of the gas at 0° Cent. or 32° Fahr., we shall have $v_0 = \frac{1}{D_0}$ and substituting in the last formula we have—

$$PV = \frac{P_0}{T_0 D_0} T$$

For air $D_0 = .080728$ lbs., $P_0 = 2116.5$ lbs. and $t_0 = 491.4$ Fahr.,

$$\frac{P_0}{T_0 D_0} = R = 53.354; \text{ hence } PV = RT = 53.354 T$$

Again, if $D_0 = .080728$ lbs., $P_0 = 2116.5$ lbs. and $t_0 = 273^\circ$ Cent.

$$\frac{P_0}{T_0 D_0} = 96.0376 \text{ and } PV = RT = 96.0376 T$$

Since $v = \frac{1}{D}$ (*i.e.*, one pound divided by the weight of one cubic foot) we can substitute and write for air

$$\frac{P}{D} = RT$$

and for any other gas,

$$\frac{P}{D'} = R'T$$

* See Note A, Appendix.

Dividing the first of these last two equations by the second, member by member, we have—

$$\frac{D'}{D} = \frac{R}{R'}$$

i.e., the constants R and R' are inversely proportional to the corresponding densities.

Taking air as a standard $\frac{D'}{D} = s$ will represent the specific gravity of a gas whose density is D' , hence

$$\frac{R}{R'} = s \text{ and } R' = \frac{R}{s}$$

Therefore, when the constant R for air is known, the constant R' for any other gas may be found by dividing R by the specific gravity s of the gas.

81. The following table gives values of s and R for the substances named:

VII.

	Specific Gravity. S	Values of R.	
		Centigrade.	Fahrenheit.
Atmospheric air.....	1.00000	96.0376	53.354
Nitrogen.....	.97137	98.867	54.926
Oxygen.....	1.10563	86.862	48.257
Hydrogen.....	.06926	1386.579	770.322
Steam-gas (ideal) (Rankine)..	.62209	154.379	85.766
“ “ “ (Zeuner) ..	.62300	154.153	85.641
“ saturated (Zeuner)...	.64000	150.160	83.422

82. The equation $pv = R(459.4 + t)$ may thus be applied to any perfect gas whose specific gravity is known.

If in this equation for the same gas we suppose t to become equal to -459.4 , the second member will become equal to zero, and under these circumstances the first member must be zero also. And as v cannot be zero because the gas cannot be annihilated, the only supposition which will reduce the product pv to zero is that p shall become zero. In other words, the elasticity of the gas disappears.

This supposes that the temperature of the gas has been reduced to the point which has been referred to as absolute cold, *i.e.*, where the heat-motions or oscillations entirely disappear and the body is without heat. The supposition that t becomes at this point -273 on the Centigrade thermometer and -459.4

Fahr., shows that this point is far from being beyond imaginable limits, although thus far it has not been practically realized.

83. The Centigrade thermometer, it is well known, is an ordinary glass-bulb thermometer, on the stem of which degrees of temperature are marked; the melting-point of ice being 0° , and the boiling-point of water 100° , and the interval being divided into 100 parts or degrees. If the graduated scale could be extended downwards so as to include—273 of these degrees below the 0, we should reach the absolute zero. In the Fahrenheit thermometer the interval between the melting-point of ice and boiling-point of water is divided into 180 equal parts or degrees, but each interval or degree is thus smaller than the Centigrade degree, one degree of C. being equal to 1.8 degree Fahr., and the zero of the scale is placed 32 degrees below the melting point of ice.

84. To reduce Fahrenheit to Centigrade, and the reverse, the following formulæ may be used:

$$c. = (F - 32) \frac{5}{9} = (F - 32) \frac{1}{1.8}$$

$$F. = \frac{9}{5} c. + 32 = 1.8 c. + 32$$

The following scale will show the position of the absolute zero on these scales:

Absolute Scale.	Centigrade.	Fahrenheit.
Cent. Fahr.		
400. 720.....	+ 127.....	+ 260.6
373. 671.4.....	+ 100.....	+ 212.....boiling-point of water.
300° 540°.....	+ 27.....	+ 80.6
273. 491.4.....	0.....	+ 32.....melting-point of ice.
255. 459.4.....	17.8.....	0
200. 360.....	73.....	99.4
100. 180.....	173.....	279.4
0. 0.....	273.....	459.4..... absolute cold.

These scales show that the absolute temperature of any body may be found from its temperature in Centigrade degrees by adding 273, and for Fahr. by adding 459.4. Calling τ the absolute temperature of a body, and t the temperature on either scale, the absolute temperature will always be

$$\tau = 273 + t \text{ for Centigrade scale.}$$

$$\tau = 459.4 + t \text{ for Fahrenheit scale.}$$

85. Returning again to the equation which expresses Mariotte's law:—

$$PV = R(459.4 + t)$$

If we suppose the pressure or elasticity of the gas and its volume both to change with a given change of temperature, we will have the relation expressed thus: $P'V' = R(459.4 + t)$ and, dividing the first equation by the second, member by member, we have—

$$\frac{PV}{P'V'} = \frac{459.4 + t}{459.4 + t'} = \frac{T}{T'} \text{ or } \frac{PV}{P'V'} = \frac{T}{T'}$$

Thus when absolute temperatures are employed for the same gas we have the ratio of the products of the pressure by the volume equal to the ratio of the absolute temperatures.

If the pressure remain the same during a change of volume and temperature, $\frac{V}{V'} = \frac{T}{T'}$, that is, under constant pressure,

the volumes occupied by a given weight of a perfect gas are proportional to the absolute temperatures. If the volumes remain constant, as when the gas is enclosed within a space which

cannot change its volume, we have $\frac{P}{P'} = \frac{T}{T'}$

we also have from the expression

$$\frac{PV}{P'V'} = \frac{T}{T'}$$

$$\frac{V}{V'} = \frac{P'}{P} \times \frac{T}{T'}$$

This equation shows that if the absolute temperature remain the same, or $\frac{T}{T'} = 1$, the volumes are inversely proportional to the pressures.

86. The following problems will illustrate the use of these expressions :

Let v_0 be the volume of a given weight of gas at 0°C. , or at 32°Fahr. (the melting-point of ice), and P_0 its elastic force at the same temperature. Also let v_1 and P_1 be the volume and elastic force at any absolute temperature T_1 , and let T_0 be the temperature on the absolute scale of the zero of the C. or Fahr. thermometer = 273°C. or $459.4 + 32 = 491.4 \text{ Fahr.}$

Then we shall have—

$$P_0 v_0 = R T_0$$

$$P_1 v_1 = R T_1$$

$$\frac{P_0 v_0}{P_1 v_1} = \frac{T_0}{T_1}$$

and

$$v_1 = \frac{P_0 v_0}{P_1} \cdot \frac{T_1}{T_0}$$

$$P_1 = \frac{P_0 v_0}{v_1} \cdot \frac{T_1}{T_0}$$

If P_2 and v_2 represent the elastic force and volume at any third absolute temperature we shall have—

$$P_2 v_2 = R T_2$$

$$\frac{P_1 v_1}{P_2 v_2} = \frac{T_1}{T_2}$$

and

$$v_2 = \frac{P_1 v_1}{P_2} \cdot \frac{T_2}{T_1}$$

$$P_2 = \frac{P_1 v_1}{v_2} \cdot \frac{T_2}{T_1}$$

If v be the volume of a unit of weight, as, for instance, the volume of one pound of the gas, or technically the *specific volume*, we may introduce the weight of a unit of volume, or the *specific weight*, as, for instance, the weight of a cubic foot.

If we designate the weight of a cubic foot or the *density* by D , we shall have, as has been already stated, $v \times D = 1$, and in-

stead of v we may substitute $\frac{1}{D}$ in the equation $P v = R T$, which will give

$$P \times \frac{1}{D} = R T$$

and for any other pressure and temperature

$$P_1 \times \frac{1}{D_1} = R T_1$$

from which may be deduced the expression

$$\frac{P}{P_1} \cdot \frac{D_1}{D} = \frac{T}{T_1}$$

and

$$D_1 = \frac{P_1 D}{P} \cdot \frac{T}{T_1}$$

from which the density D_1 for any absolute temperature T_1 may be found in terms of the temperature pressure and density at any other absolute temperature.

87. In the expression $P V = R T$, if the unit of surface be a square foot, V will represent a cubic foot, and if P represents the pressure upon a square inch, V will represent a cubic inch. The pressure P may be estimated numerically in different modes, either in pounds per square foot or inch, or by the height of a column of fluid of uniform density, the base of which is a square foot or square inch.

88. In technical applications the fluids usually employed in gauges for observing pressures are mercury and water, and the equivalent values for P in pounds in heights of a column of mercury and of a column of water will be the height in feet or inches of a column of these substances, which by its weight will give the pressure P , and the ratio of the heights will be the same as the ratio of the pressures: the simple rule for any fluid being, that the height of the column multiplied by the density of the fluid (or weight of unit of volume) shall give the numerical value of the pressure in pounds per unit of area.

Tables of comparison of various units may be found in Rankine's Rules and Tables, page 103.

89. In the expression $P V = R T$, $P V$ indicates a condition of actual energy, the pressure or elastic force arising, according to the dynamic theory of heat, from the impact of the heavy particles against the sides of the enclosure. The values of the quantity

$R = \frac{P V}{T}$ for the melting-point of ice for different gases are given,

page 26. These values express in foot-pounds the energy exerted by one pound of the different gases in expanding, at constant pressure, an amount corresponding to 1° Fahr. or 1° Centigrade.

90. If a given quantity of a perfect gas, at any temperature and pressure, be suddenly compressed, the first effect, as is well known from experiment, is to increase this energy. The volume is diminished and the pressure increased in such a manner that $p v$ is at first increased, and becomes equal to $p \tau'$, τ' being greater than τ . But if the vessel in which compression takes place be allowed to stand for some time, the product returns to its original value, $p \tau$. The heat generated by the work of compression being dissipated, the actual energy remains as it was before, and it might be supposed that all the work of compression has been lost. But while the value of the product $p v$ has not changed, the separate factors have changed, p becoming greater and v smaller, and the gas has assumed a new condition of *potential* energy compared with its former condition. In this respect it acts like a spring which has been compressed and held in place by a constant force.*

If a gas be allowed to expand suddenly by a reduction of external pressure, the heat which was dissipated is not restored, and a loss of work occurs. This is the actual occurrence in engines which utilize compressed air. The work performed by the expansion is performed at the expense of the heat of the gas or air itself, and its final temperature is restored only after it passes away from the engine, involving a loss.

If the expansion could take place under such circumstances that the heat which was dissipated after the compression (due to the work of compression) could be restored by a natural process from the surrounding bodies to which it was imparted, no loss would occur. This condition is, however, impracticable.

91. The relations which subsist between the temperatures,

* The elastic force of a spring is not dissipated, but acts promptly and suddenly when the force which retains it is removed. Compressed gas acts in the same manner, except that, to be restored to the same condition as before the compression, performing work equal to the work of compression, all the heat which was dissipated must be restored by surrounding bodies—a *process which requires time*; and therefore a compressed gas is not a true reciprocating force in machinery.

pressures, and volumes of a perfect gas have been considered under the suppositions that these quantities are respectively constant in succession.

It is often necessary to discuss problems the conditions of which require all three of these quantities to vary simultaneously. In the case just presented, the compression of air, and the subsequent utilization of it as a source of energy in an engine, such conditions are presented.

The compression may take place in such a manner that during the compression the temperature of the gas or air is increased, or it may take place in such a manner that the temperature remains constant, as when a current of cold water is used freely to abstract the heat. In all cases the final temperature usually returns to the original temperature, and the problem, as far as pressure and volume are concerned, is a simple one, following the law that the volumes are inversely as the pressures. The quantity of heat evolved will be the exact equivalent of the external work performed.

Applying the fundamental expression for perfect gases,

$$Q = \frac{A + C}{772}$$

In this case the term A , which denotes loss or gain of living force, is zero, because, in the final state of the gas, the *temperature* which represents the *vis viva* due to the molecular motions is unchanged. The work c is negative, and the equation reduces to

$$-Q = \frac{-C}{772} \text{ or } Q = \frac{C}{772}$$

conversely, where heat is transferred to a gas all the heat will be transformed into external work when a given quantity of a perfect gas passes from one state of equilibrium to another, and when the temperatures of the two limiting states are the same, whatever be the mode of expansion.

In an engine, however, the expansion takes place suddenly, and there is a depression of the temperature of the gas, if no heat be transferred to it, and the work performed by an expanding gas under these circumstances will depend upon the relations between p , v and t .

These relations are expressed by the following equations :

$$\frac{P_1}{P_0} = \left(\frac{V_0}{V_1} \right)^k \quad \text{and} \quad \frac{T_1}{T_0} = \left(\frac{V_0}{V_1} \right)^{k-1}$$

from which are deduced

$$\begin{aligned} P_1 &= P_0 \left(\frac{V_0}{V_1} \right)^k & P_1 &= P_0 \left(\frac{T_1}{T_0} \right)^{\frac{k}{k-1}} \\ V_1 &= V_0 \left(\frac{P_0}{P_1} \right)^{\frac{1}{k}} & V_1 &= V_0 \left(\frac{T_0}{T_1} \right)^{\frac{1}{k-1}} \\ T_1 &= T_0 \left(\frac{V_0}{V_1} \right)^{k-1} & T_1 &= T_0 \left(\frac{P_1}{P_0} \right)^{\frac{k-1}{k}} \end{aligned}$$

in which κ is the ratio of the specific heat of a perfect gas under *constant pressure* to its specific heat under a *constant volume*. For air the ratio of the apparent to the real specific heat is equal to

$$\frac{C_p}{C_v} = 1.408$$

the values of the exponents will then be numerically

$$\begin{aligned} k &= 1.408 & \frac{k}{k-1} &= 3.451 \\ k-1 &= .408 & \frac{1}{k} &= .71 \\ \frac{1}{k-1} &= 2.451 & \frac{k-1}{k} &= .29 \end{aligned}$$

The work of expansion and the heat lost by the gas in units of work will be expressed by

$$Q \times 772 = W = P_1 V_1 \left(\frac{V_0^{k-1} - V_1^{k-1}}{(k-1) V_0^{k-1}} \right)$$

VAPORS.

92. It is well known, from common observation, that many liquids, such as water, alcohol, and ether, if not confined in close vessels, become transformed into a condition resembling the gaseous condition at ordinary temperatures, and disappear *as liquids*, being diffused in the atmosphere as vapors. This transformation takes place in nearly all liquids more or less rapidly at ordinary temperatures, though for some no such transformation takes place at very low temperatures. It is considered probable, however, that this quiet change takes place in all liquids above certain fixed temperatures. Many solids, also,

e.g., ice and camphor, pass to the state of vapor without passing through the intermediate liquid state, under certain conditions.

If a *closed* vessel be partly filled with a liquid, the space above the liquid will thus ordinarily become filled with the vapor of the liquid, and the *elastic force* of the vapor will depend on the nature or *kind* of liquid, the *volume* of the enclosed space, and the *temperature*. If heat be applied to the liquid in this condition, the formation of vapor will continue, the vapor exerting a certain additional elastic force depending on the *temperature alone*, as long as there remains any liquid. Evaporation will cease when the application of heat is suspended, and, if the liquid be cooled, *condensation* will occur; so that the relative quantities of liquid and vapor, and the elastic force of the latter, in a given space and for a given liquid, are dependent on the condition of heat or *temperature* solely.

Similar phenomena will follow if the extent of the enclosed space be enlarged or contracted, the *temperature remaining the same*. If the space be enlarged, an additional quantity of the liquid will pass into the state of vapor; and if the space be contracted, a certain amount of the vapor will be reconverted into liquid.

93. For every liquid in an enclosed space there is thus a certain tension or elastic force depending on the temperature (whatever be the relative volumes of the liquid and the free space above it) which is the greatest elastic force that the vapor can have at each particular temperature. If the vapor be compressed, liquid is formed by condensation, and if the space be enlarged, or the external pressure which confines the vapor be diminished, additional vapor will be formed, and the elastic force will remain thus constant for each constant temperature.

94. A vapor in this condition in presence of its liquid is said to be *saturated*. Properly speaking, it is the space which is *saturated*, *i.e.*, it contains the greatest quantity of vapor possible at the given temperature.

95. This law of vapors, *viz.*, that the elastic force in a given volume depends solely on the temperature, is approximately true, whether the space in which the vapor is formed be *vacuous*, or whether it contain air or any other permanent gas, provided that the liquid exerts no solvent or chemical action on the gas.

96. The combined elastic forces, or the resultant pressure on

the sides of the vessel, when a permanent gas is present which is not acted upon by the liquid, is nearly the sum of the elastic force of the gas, and the maximum tension of the vapor at the given temperature. It was found by Regnault, in experiments on this subject, that liquids do not give off vapor of quite so great a tension in a space occupied by a permanent gas as they do in a vacuum, and that the difference increases as the temperature rises; but for technical applications, under ordinary temperatures, the law may be considered true.

The only difference between evaporation in a vacuum and in a space occupied by a gas is, that the formation of vapor takes place more slowly, if a gas be present, a fact of great importance in the economy of nature connected with the evaporation of water from the surface of the earth.

97. When heat is continuously applied to a liquid in a closed vessel, the space enclosed remaining constant, the temperature of the liquid and vapor will continually increase if there be no dissipation of heat through the sides of the vessel; the quantity of the liquid will diminish and the pressure will increase, the vapor remaining saturated as long as any liquid remains. After the last element of liquid shall have passed to the state of vapor, if heat be still applied the vapor begins to assume the properties of the permanent gases. Under this condition, if the temperature could be indefinitely raised, or the volume of the space indefinitely increased, under a constant temperature, the vapor would finally arrive at a state corresponding to that of perfect gas, and would then follow strictly the law of Mariotte and Gay-Lussac; and hence it may be said that the physical properties of vapors, when sufficiently expanded or at sufficiently high temperatures, and when they are not in contact with their liquids, are identical with those of perfect gases.

98. **Complete Vaporization.**—The temperature at which the complete evaporation of a liquid in a given space will occur depends on the relative volumes of the liquid and the space above it. With alcohol, the empty space being about equal to that occupied by the liquid, complete vaporization takes place at about 400° Fahr. In the case of water, if the space occupied by the water be about one-fourth of the whole internal volume of the vessel, the liquid will be wholly converted into vapor, if the vessel be strong enough to resist the pressure, at about 680° Fahr. (Cagniard de la Tour.)

99. The tension of the vapors of *mixed liquids*, as determined by Regnault, is the sum of the tensions of the two vapors taken separately, if the liquids have no solvent action on each other. With water and ether, the tension of the vapor of the mixture is less than that of the sum of the tensions of the two liquids taken separately, being hardly equal to that of ether alone. When two liquids dissolve each other in all proportions, *e. g.* water and alcohol, the resultant tension is intermediate between the tensions of the separate liquids.

100. **Boiling-Points.**—The *boiling-point* of a liquid is an expression which usually refers to a fixed or standard pressure upon the exterior surface, the pressure of the atmosphere; and it indicates the temperature at which the elastic force of the vapor is equal to such standard pressure.

101. *Ebullition* is a phenomenon which takes place when heat is applied to the lower part of the mass of a liquid which has been heated to the boiling-point, and arises from the formation of bubbles of vapor at the point at which the heat is applied, the bubbles rising through the liquid and escaping at the free surface.

The formation of such bubbles may occur before the whole mass of the liquid has been heated to the boiling-point, but in this case the bubbles are usually condensed before they reach the surface.

102. "**Boiling-Point due to the Pressure**"—is an expression sometimes employed to designate the *temperature* corresponding to the *pressure*, whether that temperature be above or below the standard temperature for which the boiling-points of the tables are determined.

The following are the boiling-points of a few of the liquids ordinarily met with, under atmospheric pressure, in degrees Fahr. :

VIII. Water.....	212°
Ether.....	96°
Alcohol.....	173°
Sulphur.....	601°
Sulphuric acid.....	630°
Mercury.....	660°
Acetic acid.....	243°

103. The boiling-point of a liquid, under any pressure, is, properly speaking, the lowest temperature at which ebullition

can occur, since there may be circumstances under which ebullition, or the formation of vapor, does not take place until the liquid has been heated many degrees above its tabulated boiling-point.

If the free surface of a liquid be covered or surrounded by another which has a higher boiling-point, the bubbles of vapor of the interior liquid having no escape, this liquid may attain a temperature higher than its ordinary boiling-point.

It was found by Dufour that globules of water suspended in oil could readily be heated to 27° Fahr. above the boiling-point under atmospheric pressure, and the vaporization of the bubble was then accomplished only by contact with some solid body which caused a sudden evaporation. In some experiments on very minute bubbles of water, he succeeded in heating the liquid to 178° C., or 352° Fahr., a temperature corresponding to a pressure of 9 atmospheres.

Prof. Donny, of Ghent, observed that water thoroughly deprived of air and sealed up in a long glass tube at atmospheric pressure could be heated to 138° C., or 280° Fahr., a temperature corresponding to 3.5 atmospheres. The evaporation was then sudden, and the water was violently thrown to the opposite end of the tube. (Watts's Chemistry.)

The retardation of ebullition in alkaline solutions is a phenomenon often observed.

104. The boiling-points of liquids are also influenced by the nature of the vessel. Water has generally a higher boiling-point by several degrees, under atmospheric pressure, in glass vessels than in iron vessels.

105. Liquids holding solid bodies in solution generally boil at higher temperatures than when the liquid is pure. The boiling-point of saturated brine at atmospheric pressure is about 226° Fahr. As a rule, it is considered that a saline solution, sea-water, for instance, has its boiling-point raised 1.2° Fahr. for each $\frac{1}{32}$ of salt that the water contains. Average sea-water contains about $\frac{1}{32}$; and the brine in marine boilers is not allowed to be concentrated more than $\frac{2}{32}$ to $\frac{3}{32}$ as determined by a salinometer. It was found by Magnus that the temperature also of the *vapor* of saline solutions is higher than that of the vapor of pure water under the same pressure, the difference being greater as the solution becomes more concentrated.

106. *Nebulous* or *vesicular* vapor is that which arises from the

condensation of particles of a vapor in the atmosphere, or in its own vapor, constituting cloud or mist. If heat be applied to vesicular vapor the condensed globules evaporate and the vapor becomes transparent, though still saturated. If heat be abstracted, new particles are condensed; the globules coalesce and fall in drops.

107. Superheated Vapor.—When a vapor at the point of saturation is removed from contact with its liquid and heated, it is said to be *superheated*.

A saturated vapor, not in contact with its liquid, may become superheated by the enlargement of the space which contains it; for it will then admit of compression without condensation, and will have a pressure, at the same temperature, inferior to that of saturated vapor, and also a temperature more elevated than that due to saturation for the same pressure. If S represent the weight of unit of volume (the density), and V the volume of unit of weight, it is evident that at the point of saturation S has its maximum and V its minimum value.

Vapors may be superheated to some extent, even when some part of the volume of the vapor is in contact with its liquid, by a sudden transfer of heat to the vapor, if the conditions are such that this heat is but slowly conducted to the liquid. Steam may thus be superheated in pipes the lower parts of which are filled with water; or in the dome or steam-chamber of a boiler. It is evident, however, that this is not a condition of equilibrium, and that, as heat reaches the liquid by conduction, new particles of vapor will be formed, if the process of superheating be suspended.

108. Spheroidal State.—It is a matter of common observation that when water is sprinkled upon the horizontal flat surface of a hot stove, the drops are not immediately converted into steam, but roll about on the heated surface, and gradually evaporate, retaining all the time the spherical, or spheroidal (flattened sphere) form. This condition is not peculiar to water, but may be experimentally demonstrated with all volatile liquids, and is usually described as the *spheroidal state*. It arises from the fact that the rapid formation of vapor makes a layer or bed of vapor on which the drop rests, and which prevents actual contact between the drop and the surface. The phenomenon may occur also whether the heated surface be liquid or metallic, the condition being that the surface shall be heated to a point

considerably above the boiling-point of the liquid drop. Experiments by Boutigny showed that the *lowest* temperature at which a metallic vessel will cause the spheroidal state is 289° F. for water, 273° F. for alcohol, and 141° F. for ether. The spheroidal condition, sometimes called "Leidenfrost's Phenomenon," illustrates an important fact in regard to the transfer of heat, which will be treated of in a subsequent chapter. It shows that for the rapid transfer of heat to a liquid there must be actual liquid contact with the heated surface—the interposition of a thin film of gas acting as an obstruction to the passage of heat.

109. **Humid Vapor.**—The vapor of water which is usually employed in industrial operations usually contains particles of water mechanically suspended in the vapor. The steam is then not only saturated but *wet*. When in the simple condition of saturated vapor, it is called *dry steam*.

110. *Steam-gas* is a term applied by some writers to superheated steam, or steam in the condition of a perfect gas.

Expansion of Dry Saturated Steam.—If dry saturated steam be enclosed in a vessel, and the volume be enlarged by extending the space in such a manner that the elastic force of the steam performs no *work*, the steam will become superheated, *i.e.*, its temperature will be, at the end of the expansion, higher than that due to the boiling-point corresponding to the pressure, and it will remain transparent.

If, however, the expansion takes place against a pressure so that there is work performed by the elastic force, condensation of a portion of the steam will take place, and the mass of steam will present a cloudy appearance. This fact was determined theoretically by Rankine and by Clausius, and experimentally by Hirn. It is supposed that no heat is communicated to, or abstracted from, the vapor during the expansion. This condensation does not take place in steam sufficiently *superheated*.

From the experiments of Fairbairn and Tate on superheated vapors, it appears that for an interval of about 18° Fahr. above the temperature due to the pressure, the coefficient of expansion of a superheated vapor is greater than that of perfect gases, but above this temperature, the relation between the volume and pressure follows closely the law of Mariotte. It is contended by Morin and Tresca (*Des Machines à Vapeur*) that the law of Mariotte, *viz.*, $p v = \text{constant}$, may in all cases be applied to the expansion of dry saturated steam without great

error, and that the weight of a cubic metre of vapor may always be taken at 0.622 of that of air at the same temperature and pressure. Clausius demonstrated, on the contrary, that this law is only approximate, unless the vapor be considerably removed from its point of condensation—a conclusion which seems to be fully confirmed by the latest investigations, especially those of Prof. Zeuner.

111. Specific Heats of Gases and Vapors.—The specific heat of a substance has already been referred to as the quantity of heat, in units of heat, necessary to cause a change of 1° in the temperature of one unit of weight of the substance at some standard temperature and pressure.

A standard temperature and pressure are necessary, because the specific heats of all substances, except perfect gases, vary slightly with the external pressure and with the temperature. The *unit of heat* in English measures to which other special units or specific heats are referred, has been defined to be the quantity of heat necessary to cause a change of 1° in 1 pound of pure water at the temperature of $39^\circ.1$ Fahr., and the specific heats of the tables are expressed in fractions of the *unit of heat*.

The expression—

$$Q = \frac{1}{772} (A + B + C)$$

which illustrates the effect of a change of heat Q in any substance, solid, liquid, or gaseous, shows that a quantity of heat added to a given quantity of any substance causes these effects, as has been already stated, viz.: increase of molecular vibration, or increase of *sensible heat*, represented by A ; change of position of the particles (overcoming forces of attraction), B ; and overcoming external pressure, C , arising from expansion or increase of volume.

From this it appears that the change of sensible heat represented by A does not include all of the heat involved in the change; and the *thermometer* will give only an *apparent* specific heat—the real specific heat being the whole heat, part of which has been expended in producing the effects B and C , representing internal and external work, and which has disappeared as heat.

If the substance can be confined to a constant volume, it is evident that these terms will vanish, and the *apparent* will be also the *real* specific heat.

In solids and liquids the amount of expansion is so small that the difference between the real and apparent specific heats is small. Nevertheless, it exhibits itself in experiments for determining specific heats, by showing an increase of specific heat as the expansion increases.

The following tables illustrate this fact.

If the *mean* specific heat is taken between 32° and 212°, they will be as shown in the first column; and if between 32° and 540° Fahr., the results are given in the second column.

IX. *Specific Heats.*

	Mean bet. 32 and 212.	Mean bet. 32 and 540.
* Iron.....	0.109	0.1218
Mercury	0.0330	0.0350
Zinc.....	0.0927	0.1015
Antimony.....	0.0507	0.0549
Silver.....	0.0557	0.0611
Copper.....	0.0949	0.1013
Platinum.....	0.0355	0.0355
Glass.....	0.1770	0.1990

For water, the increase of specific heat is

$$\begin{aligned}
 \dagger c = \text{spec. heat} &= 1. \text{ at } 0 \text{ Centigrade.} \\
 &= 1.0042 \text{ at } 50^\circ \text{ Centigrade.} \\
 &= 1.0132 \text{ " } 100^\circ \text{ " } \\
 &= 1.0262 \text{ " } 150^\circ \text{ " } \\
 &= 1.0440 \text{ " } 200^\circ \text{ " } \\
 &= 1.0568 \text{ " } 230^\circ \text{ " }
 \end{aligned}$$

For gases it has been explained that the term B disappears (being the work of overcoming the forces of attraction when the volume is increased), and the expression above reduced to

$$Q = \frac{1}{772} (A + c)$$

If now the gas be kept at constant volume, no expansion will occur, and the term c will also disappear, and the whole effect of a transfer of heat to the body will be to cause an increase, A . But if, in *addition* to the same change in A , the gas expands and performs work represented by c , the specific heat will be greater. This is called the *apparent* specific heat of the gas, and the specific heat under constant volume the *real* specific heat.

* Balfour Stewart.

† Wurtz, Dic. de Chemie.

112. The results of experiments by Regnault to determine the specific heats of gases at constant pressure are given in the following table for the substances named :

Name of Substance.	Specific heats at constant pressure.
X. Air.....	0.2377
Oxygen.....	0.2182
Nitrogen.....	0.2440
Hydrogen.....	3.4046
Carbonic Acid.....	0.2164
Carbonic Oxide.....	0.2479
Marsh Gas.....	0.5929
Ammonia.....	0.5080
Sulphuric Acid.....	0.1553

113. For specific heats of gases at constant volume direct experiments are difficult, and they have been determined only by indirect methods.

Let c be the specific heat of a gas at constant pressure, and c' the specific heat at constant volume: the value of the *ratio* $\frac{c}{c'}$, may be determined by various methods. The results of these

methods indicate that for air the ratio is $\frac{c}{c'} = 1.410 = k$, the exponent employed in the formulæ given for the expansion of gas in a previous paragraph.

For steam in the perfectly gaseous state, according to Rankine the ratio is $\frac{c}{c'} = 1.304$, and according to other writers $\frac{4}{3} = 1.333$.

The specific heat of air under constant volume, found in this manner, is 0.169.

The difference between 0.2377, the specific heat at constant pressure, and $0.169 = 0.069$, is really the *latent heat of expansion of air for 1° at 32°* .

114. By comparing the work due to the expansion of air in foot-pounds with this quantity 0.069, a theoretical verification of the mechanical equivalent of heat may be found.

Let one pound of air be subjected to a change of heat corresponding to 1° Fahr., first under constant pressure, and second under constant volume.

According to the expression $Q = \frac{A + C}{E}$, which represents, generally, the dynamic conditions of the problem, and in which E represents the dynamic equivalent of heat, we shall have, in the first case—

$$Q \times E = A + C$$

and in the second, since C disappears, being the *work due to expansion*, we have—

$$Q \times E = A$$

and

$$(Q - Q_1) E = A - A + C = C$$

$Q - Q_1$ is the difference, in units of heat, between the quantities of heat necessary to raise one pound of air 1° under the conditions of constant pressure and constant volume, and will be represented, according to the corresponding values of the specific heats, by

$$0.069 \times 1^\circ \text{ units of heat,}$$

and we shall have—

$$0.069 \times 1^\circ \times E = C = \text{work of expansion.}$$

But we have from Mariotte and Gay-Lussac's law

$$P V = 53.35 T$$

and

$$P V' = 53.35 T'$$

and

$$P (V - V') = 53.35 (T - T') = 53.35 \times 1^\circ$$

But P , the external pressure, \times by the change of volume, is the work of expansion $= C$.

Hence

$$\begin{aligned} C &= 53.35 \times 1^\circ \\ 0.069 \times 1^\circ \times E &= 53.35 \times 1^\circ \\ 0.069 \times E &= 53.35 \end{aligned}$$

and

$$E = \frac{53.35}{.069} = 773.2$$

This is a theoretical dynamic equivalent of heat, depending on the law of Mariotte and Gay-Lussac, and the values of specific heats found by experiment.

Actual direct determinations of this equivalent have been made by different investigators, with the results given below :

	Dynamic Equivalent.
V. Regnault, Moll and Van Beck ... Experiments on Air	768.6
Joule..... Friction of Water.....	772.69
" Friction of Mercury	774.08
" " " Cast Iron.....	774.99
Favre..... Friction.....	
Hirn..... Work of Steam Engine...	752.8
Joule..... Heat Evolved by Electro- Magnetic Engine.....	823.6

The number 772.69, determined by Joule, is regarded as the most satisfactory, and 772 has been adopted as the equivalent in English measures, and is often called Joule's Equivalent. Compared with the above theoretical determination, we have—

Theoretical.....	E=773.2
Experimental by Joule.....	E=772.69

Difference..... 0.51 foot-lb.

The specific heats of the vapors of water, alcohol, and ether, as determined by Regnault, are given in the following table, together with the densities at 32°, and at one atmospheric pressure:

	Density—air being unity.	Specific heat.
Vapor of Water.....	0.622.....	0.4750
" Alcohol.....	1.589.....	0.4513
" Ether.....	2.556.....	0.4810

115. In regard to the specific heats of bodies, it is maintained by Clausius that the true or real specific heat of a body would be constant if the volume were kept constant for all states, solid, liquid, and gaseous.

Rankine maintains, on the other hand, that the real specific heats remain constant if there is no change of volume, only so long as the substance retains the same state, solid, liquid, or gaseous; and that a change of specific heat occurs with a change of state, even though there is no change of volume. It is difficult to decide such a question experimentally, but the views of Clausius appear to be most in accordance with the dynamic theory of heat.

3 feet long

116. Elastic Force of Vapors.—The elastic force of saturated vapors may be illustrated experimentally by taking several barometer-tubes, filling them with mercury, and inserting them in a trough of mercury. The surface of the mercury in each tube will drop about six inches, leaving a vacuous space at the top of the tube. If now a small quantity of liquid water be passed up into this vacuous space in one tube, alcohol into another, and ether into another, the quantity of liquid being more than can be evaporated in each space at ordinary temperatures, it will be found that a portion of each liquid will be instantly evaporated, and the mercurial column will be depressed in each tube, but by different amounts. If each tube be now heated by surrounding it with warm water, the elastic force of each vapor will be increased, the mercury will descend in the tubes, and will finally press the mercurial column down to the level of the reservoir. At this point it is evident that the elastic force of each vapor is equal to that of the atmosphere, or 1 *atmosphere*. But the temperature of the liquid and vapor in each tube will be different from that in the others.

The temperature of the watery vapor will be found to be 212° Fahr., the temperature of the alcohol 173° , and the temperature of the ether 95° Fahr. These are the temperatures at which the elastic forces of these vapors are equal, respectively, to one atmosphere. At these temperatures the liquids will *boil*, under the atmospheric pressure.

If the temperatures be reduced below these points, the pressure remaining the same, a portion of the vapor in each tube will be liquefied; and, the temperatures remaining the same, if the pressure be increased above one atmosphere, a portion of each vapor will become liquefied. The tension or elastic force of one atmosphere is thus the *maximum tension* which the saturated vapors can bear at the temperatures given above.

If the three tubes could be enclosed in a chamber in which, by compression of the air, different pressures can be obtained higher than one atmosphere, it would be found that, for each of the substances named, the temperatures at which the mercury will be forced down to the level of the reservoir under each additional atmosphere of pressure, will be increased.

117. The following table gives the results of experiments by Regnault for the liquids named:

XI.

Pressure in Atmospheres.	Temperature of the saturated vapor in deg. Fahr.		
	Water.	Alcohol.	Ether.
1.....	212°	173°	95°
2.....	248°	206°	133°
3.....	272°	227°	157°
4.....	291°	244°	176°
5.....	306°	257°	192°
6.....	318.5	269°	206°
7.....	329.5	280°	218°
8.....	339°	288°	228°
9.....	348°	297°	238°
10.....	357°	305°	247°

The numbers of this table are taken from Zeuner's work, "de la Chaleur," French edition; the temperatures being converted from C. to F.

118. The elastic force of saturated vapors is thus *independent of the volume and proportion of liquid mixed with the vapor, and depends only on the temperature.*

119. It has been found impossible to determine, *theoretically*, the relation which the temperatures bear to the pressures, and reliance is placed mainly on the celebrated experiments of Regnault. On account of the universal employment of steam in practical applications, the importance of the results can hardly be sufficiently estimated. Regnault's tables, in fact, constitute the basis of all theoretical applications of heat through the medium of steam; giving as they do, in exact figures, the elastic force of saturated steam for all usual temperatures.

These tables show that no *simple* relation exists between the maximum tension and the temperature. Different empirical formulas have been proposed, however, to express this relation with certain degrees of approximation.

Some of these are convenient for use when the tables of Regnault are not at hand; while others are too complicated for ready use.

Among the simple formulas, the following are mentioned in the admirable work of Morin and Tresca, "des Machines à Vapeur. Vol. I. Production de la Vapeur."

N representing the pressure in atmospheres, and t the temperature in degrees Centigrade, the formulas are as follows :

Formula of Dalton.

$$t=100. + \frac{\log. N}{0.0132} \quad N=1.309. t^{-100}$$

Formula of Tredgold.

$$t=175 \sqrt[6]{N} - 75 \quad N=\left(\frac{t+75}{175}\right)^6$$

Formula of Roche.

$$\left\{ \begin{array}{l} t=100 + \frac{\log. N}{0.01494 - 0.00277 \log. N} \\ N=1.035 \frac{t-100}{1+0.002727(t-100)} \end{array} \right.$$

Formula of Coriolis.

$$\left\{ \begin{array}{l} t = \frac{2.878 \sqrt[5.355]{N} - 1}{0.01878} \\ N = \left(\frac{1 + 0.01878}{2.878} \right)^{5.355} \end{array} \right. *$$

Formula of Arago and Dulong.

$$t=100. + \frac{\sqrt[5]{N-1}}{0.007153} \quad N=(0.007153 + 0.2847)^5 *$$

Of these formulas that of Tredgold appears the most simple and exact.

The formula of Regnault is the only one which is perfectly exact. It is not given here, being too complicated for general use, but may be referred to in the work above cited.

The following table of comparisons, taken from Morin and Tresca, shows the degrees of exactness of the different formulas :

* Must be an error : For t must be a factor in the value of N .

TABLE XII.

Comparison between the values of the Temperatures according to the different Formulas.

Pressures in Atmospheres.	Temperatures observed by Regnault.	Formula of Dalton.	Formula of Tredgold.	Formula of Roche.	Formula of Coriolis.	Formula of Arago and Dulong.
1	100.	100.	100.0	100.0	100.0	100.0
2	120.6	122.7	121.4	121.3	121.2	120.8
5	152.2	152.9	153.8	153.6	153.7	153.1
10	180.3	175.8	181.9	182.6	182.8	181.8
15	198.8	189.1	200.9	200.4	200.9	200.5
20	213.0	198.6	213.3	214.2	215.5	214.6
25	224.7	205.9	224.3	230.4	226.3	226.3

120. **Regnault's Experiments.**—The following table of temperatures and pressures has been prepared from the corresponding tables given by Morin and Tresca as the results of Regnault's experiments on the pressures and temperatures of saturated steam; the necessary transformations and interpolations having been made to give the temperatures in degrees Fahr., and the pressures in pounds per square inch:

TABLE XIII.

Table of pressures of the saturated vapor of Water, from 32° to 446° Fahrenheit, from the experiments of Regnault.

Temp. Fahr.	Pressures in Atmospheres.	Pressures in lbs. per sq. inch.	Differences.	Temp. Fahr.	Pressures in Atmospheres.	Pressures in lbs. per sq. inch.	Differences.
32	0.006	0.09	0.00	49	0.011	0.17	0.01
33	0.006	0.09	0.00	50	0.012	0.18	0.00
34	0.006	0.09	0.01	51	0.012	0.18	0.01
35	0.007	0.10	0.00	52	0.013	0.19	0.01
36	0.007	0.10	0.01	53	0.013	0.20	0.01
37	0.007	0.11	0.01	54	0.014	0.21	0.00
38	0.008	0.12	0.00	55	0.014	0.21	0.01
39	0.008	0.12	0.01	56	0.015	0.22	0.02
40	0.009	0.13	0.00	57	0.016	0.24	0.00
41	0.009	0.13	0.01	58	0.016	0.24	0.01
42	0.009	0.14	0.00	59	0.017	0.25	0.01
43	0.009	0.14	0.01	60	0.018	0.26	0.00
44	0.010	0.15	0.00	61	0.018	0.26	0.00
45	0.010	0.15	0.01	62	0.018	0.26	0.02
46	0.011	0.16	0.00	63	0.019	0.28	0.01
47	0.011	0.16	0.01	64	0.020	0.29	0.00
48	0.011	0.17	0.00	65	0.020	0.29	0.02

TABLE XIII.—*Continued.*

Temp. Fahr.	Pressures in Atmospheres.	Pressures in lbs. per sq. inch.	Differ- ences.	Temp. Fahr.	Pressures in Atmospheres.	Pressures in lbs. per sq. inch.	Differ- ences.
66	0.021	0.31	0.01	117	0.105	1.54	0.03
67	0.022	0.32	0.02	118	0.107	1.57	0.08
68	0.023	0.34	0.00	119	0.112	1.65	0.03
69	0.023	0.34	0.01	120	0.114	1.68	0.04
70	0.024	0.35	0.00	121	0.117	1.72	0.06
71	0.024	0.35	0.02	122	0.121	1.78	0.04
72	0.025	0.37	0.01	123	0.124	1.82	0.05
73	0.026	0.38	0.02	124	0.127	1.87	0.04
74	0.027	0.40	0.01	125	0.130	1.91	0.09
75	0.028	0.41	0.02	126	0.136	2.00	0.04
76	0.029	0.43	0.03	127	0.139	2.04	0.05
77	0.031	0.46	0.00	128	0.142	2.09	0.06
78	0.031	0.46	0.01	129	0.146	2.15	0.05
79	0.032	0.47	0.00	130	0.150	2.20	0.06
80	0.032	0.47	0.02	131	0.154	2.26	0.06
81	0.033	0.49	0.01	132	0.158	2.32	0.06
82	0.034	0.50	0.03	133	0.162	2.38	0.06
83	0.036	0.53	0.01	134	0.166	2.44	0.09
84	0.037	0.54	0.03	135	0.172	2.53	0.04
85	0.039	0.57	0.03	136	0.175	2.57	0.09
86	0.041	0.60	0.02	137	0.181	2.66	0.03
87	0.042	0.62	0.01	138	0.183	2.69	0.12
88	0.043	0.63	0.02	139	0.191	2.81	0.07
89	0.044	0.65	0.03	140	0.196	2.88	0.06
90	0.046	0.68	0.03	141	0.200	2.94	0.07
91	0.048	0.71	0.01	142	0.205	3.01	0.08
92	0.049	0.72	0.02	143	0.210	3.09	0.10
93	0.050	0.74	0.02	144	0.217	3.19	0.04
94	0.052	0.76	0.05	145	0.220	3.23	0.09
95	0.055	0.81	0.03	146	0.226	3.32	0.08
96	0.057	0.84	0.01	147	0.231	3.40	0.10
97	0.058	0.85	0.05	148	0.238	3.50	0.10
98	0.061	0.90	0.00	149	0.245	3.60	0.09
99	0.061	0.90	0.03	150	0.251	3.69	0.12
100	0.063	0.93	0.04	151	0.259	3.81	0.09
101	0.066	0.97	0.01	152	0.265	3.90	0.08
102	0.067	0.98	0.03	153	0.271	3.98	0.11
103	0.069	1.01	0.05	154	0.278	4.09	0.10
104	0.072	1.06	0.03	155	0.285	4.19	0.06
105	0.074	1.09	0.06	156	0.289	4.25	0.16
106	0.078	1.15	0.01	157	0.300	4.41	0.09
107	0.079	1.16	0.02	158	0.306	4.50	0.03
108	0.080	1.18	0.04	159	0.308	4.53	0.14
109	0.083	1.22	0.04	160	0.318	4.67	0.11
110	0.086	1.26	0.03	161	0.325	4.78	0.19
111	0.088	1.29	0.05	162	0.338	4.97	0.10
112	0.091	1.34	0.03	163	0.345	5.07	0.12
113	0.093	1.37	0.03	164	0.353	5.19	0.12
114	0.095	1.40	0.07	165	0.361	5.31	0.14
115	0.100	1.47	0.03	166	0.371	5.45	0.12
116	0.102	1.50	0.04	167	0.379	5.57	1.02

TABLE XIII.—*Continued.*

Temp. degrees Fahr.	Pressure in Atmospheres.	Pressure in lbs. per sq. inch.	Differ- ences.	Temp. degrees Fahr.	Pressure in Atmospheres.	Pressure in lbs. per sq. inch.	Differ- ences.
168	0.387	5.69	0.13	219	1.147	16.86	0.32
169	0.396	5.82	0.13	220	1.169	17.18	0.33
170	0.405	5.95	0.15	221	1.191	17.51	0.35
171	0.415	6.10	0.15	222	1.215	17.86	0.34
172	0.425	6.25	0.16	223	1.238	18.20	0.34
173	0.436	6.41	0.13	224	1.261	18.54	0.35
174	0.445	6.54	0.15	225	1.285	18.89	0.35
175	0.455	6.69	0.16	226	1.309	19.24	0.37
176	0.466	6.85	0.15	227	1.334	19.61	0.37
177	0.476	7.00	0.15	228	1.359	19.98	0.38
178	0.488	7.15	0.21	229	1.385	20.36	0.44
179	0.501	7.36	0.18	230	1.415	20.80	0.40
180	0.513	7.54	0.12	231	1.442	21.20	0.39
181	0.521	7.66	0.15	232	1.469	21.59	0.42
182	0.531	7.81	0.17	233	1.497	22.01	0.41
183	0.543	7.98	0.19	234	1.525	22.42	0.41
184	0.556	8.17	0.19	235	1.553	22.83	0.43
185	0.569	8.36	0.18	236	1.582	23.26	0.44
186	0.581	8.54	0.18	237	1.612	23.70	0.42
187	0.593	8.72	0.17	238	1.641	24.12	0.43
188	0.605	8.89	0.19	239	1.670	24.55	0.44
189	0.618	9.08	0.21	240	1.700	24.99	0.45
190	0.632	9.29	0.21	241	1.731	25.45	0.45
191	0.646	9.50	0.22	242	1.762	25.90	0.47
192	0.661	9.72	0.22	243	1.794	26.37	0.47
193	0.676	9.94	0.22	244	1.826	26.84	0.49
194	0.691	10.16	0.20	245	1.859	27.33	0.50
195	0.705	10.36	0.21	246	1.893	27.83	0.51
196	0.719	10.57	0.22	247	1.928	28.34	0.50
197	0.734	10.79	0.22	248	1.962	28.84	0.52
198	0.749	11.01	0.22	249	1.997	29.36	0.51
199	0.764	11.23	0.22	250	2.032	29.87	0.53
200	0.770	11.45	0.12	251	2.068	30.40	0.53
201	0.787	11.57	0.25	252	2.104	30.93	0.54
202	0.804	11.82	0.43	253	2.141	31.47	0.56
203	0.833	12.25	0.25	254	2.179	32.03	0.57
204	0.850	12.50	0.24	255	2.217	32.60	0.56
205	0.867	12.74	0.27	256	2.256	33.16	0.56
206	0.885	13.01	0.28	257	2.294	33.72	0.59
207	0.904	13.29	0.28	258	2.334	34.31	0.59
208	0.923	13.57	0.28	259	2.374	34.90	0.60
209	0.942	13.85	0.28	260	2.415	35.50	0.60
210	0.961	14.13	0.29	261	2.456	36.10	0.62
211	0.981	14.42	0.28	262	2.498	36.72	0.63
212	1.000	14.71	0.30	263	2.541	37.35	0.63
213	1.020	15.00	0.29	264	2.584	37.98	0.64
214	1.040	15.29	0.31	265	2.627	38.62	0.64
215	1.061	15.60	0.32	266	2.671	39.26	0.67
216	1.083	15.92	0.31	267	2.716	39.93	0.66
217	1.104	16.23	0.31	268	2.761	40.59	0.67
218	1.125	16.54	0.32	269	2.807	41.26	0.69

TABLE XIII.—*Continued.*

Temp. degrees Fahr.	Pressure in Atmospheres.	Pressure in lbs. per sq. inch.	Differ- ences.	Temp. degrees Fahr.	Pressure in Atmospheres.	Pressure in lbs. per sq. inch.	Differ- ences.
270	2.854	41.95	0.69	321	6.208	91.26	1.29
271	2.901	42.64	0.71	322	6.296	92.55	1.31
272	2.949	43.35	0.71	323	6.385	93.86	1.32
273	2.997	44.06	0.72	324	6.475	95.18	1.34
274	3.046	44.78	0.75	325	6.566	96.52	1.35
275	3.097	45.53	0.73	326	6.658	97.87	1.37
276	3.147	46.26	0.75	327	6.751	99.24	1.40
277	3.198	47.01	0.77	328	6.846	100.64	1.45
278	3.250	47.78	0.77	329	6.945	102.09	1.44
279	3.303	48.55	0.80	330	7.043	103.53	1.44
280	3.357	49.35	0.79	331	7.141	104.97	1.44
281	3.411	50.14	0.81	332	7.239	106.41	1.46
282	3.466	50.95	0.81	333	7.338	107.87	1.45
283	3.521	51.76	0.81	334	7.437	109.32	1.46
284	3.576	52.57	0.82	335	7.536	110.78	1.50
285	3.632	53.39	0.84	336	7.638	112.28	1.51
286	3.689	54.23	0.85	337	7.741	113.79	1.55
287	3.747	55.08	0.87	338	7.846	115.34	1.55
288	3.806	55.95	0.88	339	7.952	116.89	1.59
289	3.866	56.83	0.88	340	8.060	118.48	1.60
290	3.926	57.71	0.90	341	8.169	120.08	1.62
291	3.987	58.61	0.91	342	8.279	121.70	1.62
292	4.049	59.52	0.93	343	8.389	123.32	1.63
293	4.112	60.45	0.92	344	8.500	124.95	1.65
294	4.175	61.37	0.94	345	8.612	126.60	1.64
295	4.239	62.31	0.96	346	8.724	128.24	1.68
296	4.304	63.27	0.97	347	8.838	129.92	1.69
297	4.370	64.24	0.98	348	8.953	131.61	1.72
298	4.437	65.22	1.00	349	9.070	133.33	1.75
299	4.505	66.22	1.02	350	9.189	135.08	1.78
300	4.574	67.24	1.01	351	9.310	136.86	1.81
301	4.643	68.25	1.02	352	9.433	138.67	1.80
302	4.712	69.27	1.03	353	9.556	140.47	1.83
303	4.782	70.30	1.04	354	9.680	142.30	1.82
304	4.853	71.34	1.06	355	9.804	144.12	1.84
305	4.925	72.40	1.07	356	9.929	145.96	1.85
306	4.998	73.47	1.09	357	10.055	147.81	1.87
307	5.072	74.56	1.10	358	10.182	149.68	1.89
308	5.147	75.66	1.12	359	10.311	151.57	1.93
309	5.223	76.78	1.13	360	10.442	153.50	1.95
310	5.300	77.91	1.16	361	10.575	155.45	1.99
311	5.379	79.07	1.16	362	10.710	157.44	2.01
312	5.458	80.23	1.18	363	10.847	159.45	2.03
313	5.538	81.41	1.19	364	10.985	161.48	2.03
314	5.619	82.60	1.20	365	11.123	163.51	2.04
315	5.701	83.80	1.22	366	11.262	165.55	2.04
316	5.784	85.02	1.22	367	11.401	167.59	2.08
317	5.867	86.24	1.24	368	11.542	169.67	2.08
318	5.951	87.48	1.23	369	11.684	171.75	2.14
319	6.035	88.71	1.27	370	11.829	173.89	2.16
320	6.121	89.98	1.28	371	11.976	176.05	2.19

TABLE XIII.—*Continued.*

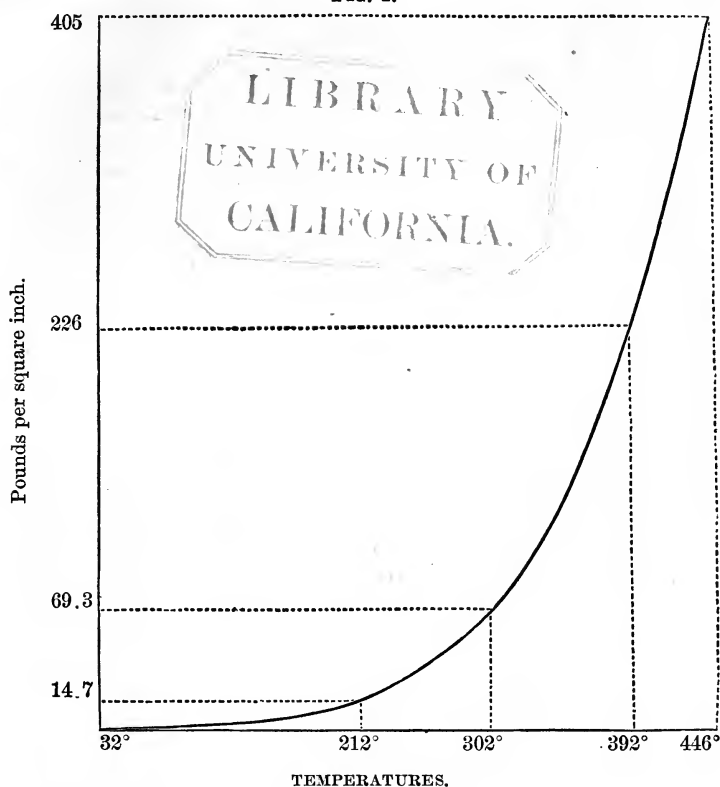
Temp. degrees Fahr.	Pressure in Atmospheres.	Pressure in lbs. per sq. inch.	Differ- ences.	Temp. degrees Fahr.	Pressure in Atmospheres.	Pressure in lbs. per sq. inch.	Differ- ences.
372	12.125	178.24	2.19	410	18.848	277.07	3.16
373	12.274	180.43	2.22	411	19.063	280.23	3.19
374	12.425	182.65	2.22	412	19.280	283.42	3.19
375	12.576	184.87	2.23	413	19.497	286.61	3.19
376	12.728	187.10	2.25	414	19.714	289.80	3.19
377	12.881	189.35	2.26	415	19.931	292.99	3.19
378	13.035	191.61	2.28	416	20.148	296.18	3.19
379	13.190	193.89	2.31	417	20.365	299.37	3.19
380	13.347	196.20	2.35	418	20.582	302.56	3.07
381	13.507	198.55	2.40	419	20.791	305.63	3.38
382	13.670	200.95	2.44	420	21.021	309.01	3.38
383	13.836	203.39	2.45	421	21.251	312.39	3.38
384	14.003	205.84	2.47	422	21.481	315.77	3.38
385	14.171	208.31	2.49	423	21.711	319.15	3.44
386	14.340	210.80	2.50	424	21.945	322.59	3.32
387	14.510	213.30	2.51	425	22.171	325.91	3.38
388	14.681	215.81	2.54	426	22.401	329.29	3.39
389	14.854	218.35	2.58	427	22.631	332.68	3.83
390	15.029	220.93	2.60	428	22.892	336.51	3.53
391	15.206	223.53	2.56	429	23.132	340.04	3.53
392	15.380	226.09	1.13	430	23.372	343.57	3.53
393	15.457	227.22	2.64	431	23.612	347.10	3.52
394	15.637	229.86	2.69	432	23.852	350.62	3.68
395	15.820	232.55	2.65	433	24.102	354.30	3.67
396	16.000	235.20	2.79	434	24.352	357.97	3.68
397	16.190	237.99	2.87	435	24.602	361.65	3.67
398	16.385	240.86	2.90	436	24.852	365.32	3.91
399	16.582	243.76	2.94	437	25.118	369.23	3.83
400	16.782	246.70	3.04	438	25.378	373.06	3.82
401	16.989	249.74	3.47	439	25.638	376.88	3.82
402	17.225	253.21	3.03	440	25.898	380.70	3.90
403	17.431	256.24	3.04	441	26.163	384.60	3.97
404	17.638	259.28	3.07	442	26.433	388.57	4.11
405	17.847	262.35	3.04	443	26.713	392.68	4.12
406	18.054	265.39	3.05	444	26.993	396.80	4.11
407	18.261	268.44	3.04	445	27.273	400.91	4.12
408	18.468	271.48	3.04	446	27.553	405.03	
409	18.675	274.52	2.55				

121. The most remarkable feature in these results is the change in the rate of increase of pressure for one degree of temperature. At about 212° , the rate of increase for one degree rise of temperature is about 0.3 of a pound; at 250° , it is 0.5 of a pound; at 300° , about 1 pound; at 350° , 1.8 pounds; at 400° , about 3 pounds; and at 446° , 4.1 pounds.

The following diagram exhibits this law to the eye at a glance. It is a graphical representation, on a small scale, of

the relation between the temperatures and pressures from Regnault's experiments.

FIG. 1.



122. It is often convenient to refer to a corresponding table in which the pressures are given in the first column, increasing by one pound—the corresponding temperatures Fahr. being introduced in the next column.

Such a table may be found in many English works, and that which is found in Fairbairn's "Mills and Mill-work" is here introduced.

The *rate of decrease of temperature* with the *pressure* is shown in the column of differences—the third column.

At 1 lb. pressure (102°) it requires a rise of temperature of 24° to increase the pressure to 2 lbs.; at 14.7 lbs. (1 atmosphere) it requires an increase of temperature of 3.5° only, for an increase 1 lb. pressure; at 30 lbs. about 2°; at 70 lbs. 1°; at 100 lbs. 0.7°; at 250 lbs. 0.4° Fahr.

TABLE XIV.

"Of the pressure and corresponding temperature of saturated steam, obtained from the tables of M. Regnault, by interpolation and reduction to English measures." (FAIRBAIRN.)

Pressure in lbs. per sq. inch.	Temp. in de- grees Fahr.	Rise of temp. for 1 lb. pres.	Pressure in lbs. per sq. inch.	Temp. in de- grees Fahr.	Rise of temp. for 1 lb. pres.	Pressure in lbs. per sq. inch.	Temp. in de- grees Fahr.	Rise of temp. for 1 lb. pres.
1	102.	24.3	32	253.9	1.8	75	307.4	0.9
2	126.3		33	255.7	1.8	80	311.8	0.9
3	141.6	15.4	34	257.5	1.7	85	316.0	0.8
4	153.1	11.5	35	259.2	1.7	90	320.0	0.8
5	162.3	9.3	36	260.8	1.6	95	323.9	0.7
6	170.1	7.8	37	262.4	1.6	100	327.6	0.7
7	176.9	6.8	38	264.0	1.5	105	331.1	0.7
8	182.9	6.0	39	265.6	1.5	110	334.5	0.7
9	188.3	5.4	40	267.1	1.5	115	337.8	0.6
10	193.2	4.9	41	268.6	1.5	120	341.0	0.6
11	197.8	4.5	42	270.1	1.4	125	344.1	0.6
12	202.0	4.2	43	271.5	1.4	130	347.1	0.6
13	205.9	3.9	44	272.9	1.4	135	350.0	0.6
14	209.6	3.7	45	274.3	1.4	140	352.8	0.6
14.7	212.		46	275.7	1.3	145	355.6	0.6
15	213.	3.5	47	277.0	1.3	150	358.3	0.5
16	216.3	3.3	48	278.3	1.3	160	363.4	0.5
17	219.4	3.1	49	279.6	1.3	170	368.2	0.5
18	222.4	3.0	50	280.9	1.3	180	372.9	0.5
19	225.2	2.8	51	282.6	1.2	190	377.5	0.4
20	227.9	2.7	52	283.3	1.2	200	381.8	0.4
21	230.5	2.6	53	284.5	1.2	210	386.0	0.4
22	233.1	2.5	54	285.7	1.2	220	389.9	0.4
23	235.5	2.3	55	286.9	1.2	230	393.8	0.4
24	237.8	2.3	56	288.1	1.1	240	397.5	0.4
25	240.0	2.3	57	289.2	1.1	250	401.1	0.3
26	242.2	2.2	58	290.3	1.1	260	404.5	0.3
27	244.3	2.1	59	291.4	1.1	270	407.9	0.3
28	246.3	2.0	60	292.5	1.1	280	411.2	0.3
29	248.3	2.	65	297.8	1.	290	414.4	0.3
30	250.2	1.9	70	302.7		300	417.5	
31	252.1	1.9						
32	253.9	1.9						

LATENT HEAT.

123. The effects which follow the transferring of heat to a body, solid, liquid, or gaseous, have been described by employing the simple algebraic expression,

$$Q = \frac{A + B + C}{772}$$

The quantity A represents a change which is exhibited by a change of sensible heat, or change of *temperature*. That part of the whole heat transferred which produces the work B and the work C is expended in producing a change in the relative positions of the particles, and in *external* work; and disappears as *sensible heat*, i.e., it is not afterwards contained in the body, or exhibited in the body, as heat. These quantities of heat represented by $\frac{B}{772}$ and $\frac{C}{772}$ become *latent*.

The term *latent heat* is a technical expression, designating a quantity of heat which has apparently disappeared, but which really has been employed in producing changes in the body, in the form of work, other than the change of velocity of molecular motion, or change of *temperature*. By reversing the process by which heat is thus made to disappear, this latent heat may be reproduced.

In thus separating the effects of a given quantity of heat Q into the parts A , B , and C , the true theories of the *coefficient of expansion*, *specific heat*, and *latent heat* become susceptible of rational explanation. Of these quantities, A and C , for any change of heat in a body, can usually be numerically estimated; the change A being directly proportional to T , the change of *absolute* temperature, and the change C being the product of the *external* pressure multiplied by the change of volume of the body. The quantity B , however, cannot thus be separately calculated, because there is not, in the present state of science, sufficient knowledge of molecular attractions to compute directly the work performed in overcoming these attractions for a given change of volume. This is not important, however, because this quantity may be found from the expression,

$$Q = \frac{A + B + C}{772}$$

when Q , A , and c are known. And, moreover, it happens in the action of bodies under the influence of heat, that in the solid and liquid forms, for nearly all bodies, the quantity c is so small for the extreme range of temperature belonging to those states, that for technical purposes it may be neglected; while, on the other hand, after the body has passed to the state of vapor or gas, the quantity c becomes large, and the quantity B , so small that it may be neglected.

The latent heat which, in the most general case, is represented by $\frac{1}{772}(B + c)$ becomes for solids and liquids, practically,

$\frac{1}{772}B$ and for gases, especially perfect gases, $\frac{1}{772}c$. In other words, in the case of *solids* and *liquids*, for all practical purposes, the effect of the exterior pressure may be neglected, and in the case of perfect gases and vapors, the *internal work* may be regarded as simply confined to the change of molecular vibration.

The *specific heat* of a *solid* or *liquid* may be regarded, therefore, as equivalent to

$$c = (a + b) \frac{1}{772}$$

$\frac{a}{772}$ being the quantity of heat, in units of heat, which remain in 1 lb. of the substance after an increase of temperature of 1° Fahr., and $\frac{b}{772}$ being the *latent heat of expansion* of 1 lb. of the substance for 1° rise of temperature.

Practically, this quantity, or the latent heat of expansion, is included in the specific heat, for ordinary solids and liquids, the quantities a and b not being separated. The amount of heat necessary to raise one pound of a solid any number of degrees in temperature is thus c , the specific heat, multiplied by t , the number of degrees, c being the *mean* specific heat of the solid for the given range of temperature.

A remarkable change occurs, however, in the relative values of the quantities A , B , and c when a body *changes its state* from solid to liquid, or from liquid to gaseous.

At the melting-point, the quantity A vanishes suddenly or gradually, and the addition of heat, after that, does not raise the temperature of the residual mass of solid, or that part which has become liquid, each additional unit of heat being expended

in the work designated by $B + c$; B being the greater, and c being usually very small, and sometimes *negative*.

124. **Latent Heat of Fusion.**—This quantity $\frac{B + c}{772}$ for each lb. of the substance *melted* is called the *latent heat of fusion*, and its value in units of heat for various substances has already been given, page 21.

After the body has all passed to the liquid state, if heat be still applied, the quantity A reappears (the substance is further heated and the temperature rises), and from the melting-point to the boiling-point the quantity of heat necessary to raise the temperature of the body 1° Fahr. is again composed of the three terms A , B , and c ; c being, as in the solid state, very small, since the expansion of liquids is small, and the specific heat of the liquid is taken to represent the combined quantities A , B , and c . The quantity of heat necessary to raise the temperature of 1 lb. of water from the melting-point of ice to the boiling-point of water being

$$q = c \times 212^\circ$$

and through any given range of temperature

$$q = c \times (t_1 - t)$$

c being the mean specific heat for the given range of temperature, and $t_1 - t$, the number of degrees.

125. **Latent Heat of Vaporization.**—At the boiling-point of a liquid, another remarkable phenomenon occurs, similar to that attending the melting of the body. The term A again vanishes, or, in other language, the temperature of the liquid and its vapor remains constant, as long as the external pressure is constant, until all the liquid has passed to the state of vapor. All the heat transferred to the substance during this transformation becomes *latent*, or is expended in producing the work represented by $B + c$.

The sum of these two quantities expressed in units of heat or $\frac{B + c}{772}$ is in this case the quantity which has received the name of *latent heat of evaporation*, and which has been determined by various investigators for different liquids and for different boiling-points. The following table gives the latent heats of evaporation, in English units, of various substances, the pressure on the external surface being one atmosphere.

Latent heat of Vaporization, in English units, at one atmosphere.

Water	966.23...	Regnault.
Ether.....	164.0 ...	Favre and Silberman.
Oil of turpentine...	123.0....	“ “
Alcohol.....	372.7....	“ “
Hydrocarbons.....	107.8....	“ “

The change from the state of liquid to the state of vapor being accompanied, at the pressures most employed, by a considerable increase of volume, the term $\frac{C}{772}$ in the general formula

$\frac{B}{772} + \frac{C}{772}$, which represents the latent heat of vaporization,

becomes appreciable. The term $\frac{B}{772}$ represents the heat employed in overcoming the attractions of the particles, by which they are entirely removed from attractive influence on each other; this constitutes the principal part of the latent heat.

While the term $\frac{C}{772}$ represents the work of overcoming the external pressure in units of heat, and may be represented by

$\frac{P U}{772}$, P representing the external pressure, and U the increase of volume which the liquid undergoes in expanding to the vaporous form; so that if L represents the total latent heat, or $\frac{B+C}{772}$, in units of heat, we may represent this by

$$L = \frac{B}{772} + \frac{P U}{772}$$

or
$$L = R + P U \frac{1}{772}$$

R representing the units of heat corresponding to $\frac{B}{772}$.

126. The latent heat of vaporization of water for different temperatures or pressures, to about 375° Fahr., was determined by Regnault, in a series of experiments no less important and valuable than those made by this celebrated physicist for determining the relation between the temperatures and pressures.

Rankine gives the following empirical formula, based on that of Regnault, which represents the results of these experiments:

$$L = 1091.7 - 0.695(t - 32^\circ) - 0.000000103(t - 39.1^\circ)^3$$

or, approximately for technical applications,

$$\begin{aligned} L &= 1092. - 0.7(t - 32^\circ) \\ &= 966 - 0.7(t - 212^\circ) \end{aligned}$$

From this formula it is apparent that the latent heat of evaporation for water diminishes with the temperature above 212° .

127. Total Heat of Vaporization.—The total heat necessary to transform one pound of water from the liquid condition at the melting-point of ice to the condition of saturated vapor or steam at the temperature t , may now be estimated. This is called the *total heat of vaporization*, and represents the sum of the heat which is required to heat the water from the temperature 32° to the temperature t , and the heat which disappears as latent heat. By algebraic symbols this sum is evidently expressed as follows:

$$Q = c(t - 32^\circ) + L = q + L$$

c being the mean specific heat of water between the limits of temperature, and L the latent heat of vaporization at the higher temperature.

128. The results of Regnault's experiments, already referred to, led him to the discovery that *the total heat of the vapor of water from the temperature of melting ice increases at a uniform rate as the temperature rises.*

Regnault's formula by which this law is expressed is as follows:

$$Q = 606.5 + 0.305 t$$

Q being the total heat in calories, and t being expressed in Centigrade degrees.

The equivalent English formula is—

$$Q = 1091.7 + 0.305.(t - 32^\circ)$$

The expression for the total heat of vaporization is—

$$Q = q + L$$

from which we have $L = Q - q$

that is, the latent heat of vaporization is equal to the total heat, diminished by the quantity of heat necessary to raise the temperature of the liquid from the melting-point of ice to the final temperature of evaporation.

In practice the specific heat of liquid water may often be regarded as unity, and q for 1 lb. of water will then be represented by $1 \times (t_1 - t)$, or $(t_1 - t)$ the difference of temperatures.

The above formula for the total heat gives the total heat necessary to raise the temperature of 1 lb. of water from 32° to any temperature and evaporate it at that temperature. Water is not usually obtained in industrial processes at so low a temperature as 32° (*e.g.*, the feed-water of steam-boilers), and is often heated, by what would otherwise be wasted heat, to a temperature as high as possible, before its introduction to the evaporating vessel.

If from the total heat as given above by the formula

$$q = 1091.7 + 0.305 (t - 32^\circ)$$

we subtract the heat necessary to raise 1 lb. of water from 32° to the temperature of the feed-water t_1 we shall have the total heat required to raise the water from the temperature t_1 to t , and evaporate it at t° Fahr.

$$q = 1091.7 + 0.305 (t - 32) - c (t_1 - 32)$$

c being the mean specific heat of water between 32° and t_1 or, approximately, c being 1, the formula may be written—

$$q = 1092. + .3 (t - 32) - (t_1 - 32)$$

129. Factor of Evaporation.—In experiments to determine the evaporative powers of given kinds of fuel, or of given boilers, for the purposes of comparison, it is necessary to refer all such experiments to the same standard conditions; and it is usual to select the condition of water supplied to a boiler at 212° Fahr. and evaporated at that temperature; at which the number of units of heat necessary for each lb. is 966. If the water is actually supplied at a lower temperature, and evaporated at a higher temperature, the quantity of water which would have been evaporated under the standard conditions of temperature, *i.e.*, from and at 212° , by the same quantity of fuel burned, may be found by a simple proportion, thus:

Let w_1 be the weight of water actually evaporated at the higher temperature by the total heat q_1 found by the above formula, and x the quantity which would have been evaporated if the water had been supplied and evaporated at 212° . Then we shall have, evidently,

$$x \cdot 966 = w_1 \cdot Q_1$$

$$\text{and} \quad x = w_1 \frac{Q_1}{966}$$

The following formula for the factor $\frac{Q_1}{966}$ for any temperature t_1 of the feed-water and any other temperature t of the evaporating point, is given by Rankine:

$$F = 1 + 0.3 \cdot \frac{(t - 212^\circ) + (212 - t_1)}{966}$$

130. Total Heat of Superheated Steam.—When dry saturated steam is superheated, it is evident, from what precedes, that the additional quantity of heat necessary to raise the temperature of 1 lb., the steam 1° will depend on the specific heat of steam. This, as determined by Regnault, is 0.475, and to heat saturated steam from the temperature t , its boiling-point, under a given pressure, to a temperature t_2 under the same constant pressure, will be $0.475 (t_2 - t)$.

So that the total heat of superheated steam may be found by the formula—

$$Q = 1091.7 + 0.305 (t - 32) + 0.475 (t_2 - t)$$

The total quantity of heat in English units necessary to raise the temperature of 1 lb. of water from 32° to a given temperature and evaporate it at that temperature has been given in the form $Q = q + z$, from which we have $z = Q - q$, in which q represents the quantity of heat required to raise the temperature of the *liquid* from 32° to the given temperature and z the quantity necessary to evaporate it at that temperature, or the latent heat of vaporization. It has been also stated that the quantity z is really composed of two terms,

$$L = R + \frac{P U}{772}$$

in which R represents that part of the latent heat which arises from the work of the heat in overcoming completely the molecular attractions, and $\frac{P U}{772}$ that part which arises from the work performed in the expansion of the volume of the liquid to the

volume of the liquid and its vapor ; the increase of volume being represented by u and the external pressure by p . The total quantity of heat required to raise 1 lb. of water from 32° to any temperature, and evaporate it at that temperature, will then be expressed by

$$Q = q + R + \frac{P U}{772}$$

In this expression q may be said to be the quantity of heat *contained in the water* at the temperature of vaporization, R the quantity of heat *contained in the vapor*, and $\frac{P U}{772}$ a quantity of heat which has been converted into *external work*.

131. The separation of the latent heat of vaporization into its two parts, and the determination of the values of these parts, is due to Prof. Zeuner, whose researches in this subject have simplified greatly the mathematical theory of the mechanical action of steam in its employment in the steam-engine.

Prof. Zeuner calls the quantity q the *heat of the liquid*, the quantity R the *internal latent heat*, and the quantity $\frac{P U}{772}$ the *external latent heat*.

If from the total quantity of heat Q we subtract the quantity $\frac{P U}{772}$ we shall have $J = Q - \frac{P U}{772}$, which is designated by Prof. Zeuner, the *heat of the vapor*. Its value indicates the *excess in units of heat of the heat contained in unit of weight of the vapor, over the heat contained in the unit of weight of the liquid at 32° Fahr. from which it was produced*.

The heat of the vapor J and the internal latent heat $R = L - \frac{P U}{772}$ are independent of the mode of evaporation, while in employing the total heat of vaporization Q , and the latent heat of evaporation L in the ordinary mode, it is necessary to suppose that the evaporation takes place under *constant pressure*.*

The quantities J and R are related to each other according to the last two expressions by the formula

$$q = J - R$$

because we have from these expressions

* Zeuner, *de la Chaleur*.

$$J - R = Q - L$$

and from a preceding formula

$$q = Q - L$$

The quantity $\frac{P U}{772}$ in the preceding formulas might be calculated from the formula of Mariotte and Gay-Lussac: $P U = R T$ for any temperature t , or any absolute temperature T , if vapors were strictly subject to the law of perfect gases; but as this formula cannot be applied, Prof. Zeuner employs another formula, based on the dynamic theory of heat, by which the value of $\frac{P U}{772}$ is found, and in which the values of L , the total latent of evaporation, are taken from the experiments of Regnault.

The values of this term having been found for different pressures and temperatures, if these values be subtracted from the total latent heat L , the results will give the corresponding values of R .

132. Table XV., pp. 64, 65, exhibits the results of calculations made by Prof. Zeuner to determine the values of R and $\frac{P U}{772}$ in the manner indicated for different pressures, from 1 to 14 atmospheres, for the vapor of water.

The same table contains the corresponding values of the quantity q , the heat of the liquid.

The table of Prof. Zeuner has been transformed from Centigrade to Fahr. and from French to English units, and the quantities given in the table refer to 1 lb. and one cubic foot as the units of weight and volume.

The numbers in this table give the numerical values of the terms of the equation

$$Q = q + R + \frac{P U}{772}$$

for 1 lb. of water and for different temperatures.

133. **Total Heat in Wet Steam.**—The quantity of heat contained in a mixture of liquid and vapor, whether the liquid be mechanically suspended in the form of minute drops, constituting *wet steam*, or whether the liquid remain in a mass at the bottom of the vessel, may be found, if the relative quantities of liquid and vapor can be determined. If x be the weight of vapor in 1 lb. of the mixture, the quantity of heat in the liquid at the

TABLE XV.

Giving the heat of the liquid, the internal latent heat, the external latent heat, the specific volume and specific weight of 1 lb. of saturated steam at different pressures.

Pressure in atmos- pheres.	Pressure in lbs. per sq. inch.	Tempera- ture in degrees Fahr.	Heat of liquid in units of heat.	Latent in- ternal heat of vapor in units of heat.	External latent heat in units of heat.	Specific volume in cu. feet.	Specific weight in lbs.
			q.	R.	$\frac{P U}{772}$		D.
0.1	1.47	115.0	83.308	969.926	63.835	233.0879	.0043
0.2	2.94	141.0	109.060	949.651	66.175	120.8162	.0083
0.3	4.41	157.0	125.437	936.779	67.633	82.3180	.0121
0.4	5.88	169.4	137.698	927.155	68.708	62.7204	.0159
0.5	7.35	178.9	147.631	919.381	69.547	50.7880	.0197
0.6	8.82	187.6	155.992	912.818	70.281	42.7705	.0234
0.7	10.29	194.6	163.267	907.123	70.897	36.9812	.0270
0.8	11.76	201.8	169.747	902.054	71.438	32.6065	.0307
0.9	13.23	206.8	175.577	897.498	71.923	29.1800	.0343
1.0	14.70	212.0	180.900	893.340	72.360	26.4216	.0378
1.1	16.17	216.8	185.789	889.524	72.758	24.1517	.0414
1.2	17.64	221.4	190.332	885.978	73.127	22.2519	.0449
1.3	19.11	225.6	194.587	882.661	73.469	20.6356	.0484
1.4	20.58	229.5	198.569	879.557	73.787	19.2451	.0519
1.5	22.05	233.1	202.334	876.625	74.086	18.0341	.0554
1.6	23.52	236.6	205.900	873.848	74.367	16.9720	.0589
1.7	24.99	240.0	209.284	871.214	74.633	16.0301	.0623
1.8	26.46	243.2	212.506	868.709	74.884	15.1907	.0658
1.9	27.93	246.2	215.602	866.302	75.121	14.4362	.0692
2.0	29.40	249.1	218.551	864.009	75.350	13.7570	.0726
2.1	30.87	251.9	221.391	861.802	75.566	13.1387	.0760
2.2	32.34	254.5	224.123	859.682	75.773	12.5764	.0794
2.3	33.81	257.1	226.746	857.646	75.973	12.0606	.0828
2.4	35.28	259.6	229.295	855.666	76.165	11.5881	.0862
2.5	36.75	262.0	231.755	853.758	76.349	11.1508	.0896
2.6	38.22	264.4	234.142	851.908	76.527	10.7471	.0929
2.7	39.69	266.6	236.437	850.127	76.698	10.3722	.0963
2.8	41.16	268.8	238.678	848.390	76.864	10.0230	.0996
2.9	42.63	271.0	240.865	846.697	77.024	9.6978	.1029
3.0	44.10	273.1	242.980	845.052	77.177	9.3935	.1063
3.1	45.57	275.0	245.039	843.464	77.328	9.1084	.1096
3.2	47.04	277.0	247.045	841.912	77.472	8.8392	.1129
3.3	48.51	278.9	249.014	840.389	77.614	8.5877	.1162
3.4	49.98	280.8	250.927	838.908	77.753	8.3507	.1195
3.5	51.45	282.6	252.788	837.470	77.884	8.1248	.1228
3.6	52.92	284.4	254.610	836.060	78.016	7.9133	.1261
3.7	54.39	286.2	256.415	834.665	78.143	7.7115	.1294
3.8	55.86	287.9	258.149	833.326	78.264	7.5209	.1327
3.9	57.33	289.6	259.862	832.003	78.386	7.3383	.1360
4.0	58.80	291.2	261.558	830.693	78.505	7.1669	.1392
4.1	60.27	292.8	263.200	829.426	78.619	7.0019	.1425
4.2	61.74	294.4	264.805	828.187	78.730	6.8449	.1458
4.3	63.21	295.9	266.373	826.976	78.838	6.6943	.1490
4.4	64.68	297.4	267.943	825.766	78.946	6.5517	.1523
4.5	66.15	298.9	269.474	824.583	79.052	6.4140	.1555
4.6	67.62	300.4	270.970	823.432	79.155	6.2826	.1587
4.7	69.09	301.8	272.448	822.292	79.254	6.1577	.1620

TABLE XV.—*Continued.*

Pressure in atmos- pheres.	Pressure in lbs. per sq. inch.	Tempera- ture in degrees Fahr.	Heat of liquid in units of heat. q.	Latent in- ternal heat of vapor in units of heat. R.	External latent heat in units of heat. $\frac{P U}{772}$	Specific volume in cu. feet. U.	Specific weight in lbs. D.
4.8	70.56	303.2	273.908	821.167	79.353	6.0859	.1652
4.9	72.03	304.6	275.330	820.071	79.450	5.9206	.1685
5.0	73.50	306.0	276.734	818.989	79.546	5.8085	.1717
5.1	74.97	307.4	278.122	817.922	79.637	5.7011	.1749
5.2	76.44	308.7	279.472	816.881	79.727	5.5986	.1781
5.3	77.91	310.0	280.822	815.843	79.817	5.4993	.1813
5.4	79.38	311.3	282.134	814.831	79.905	5.4032	.1845
5.5	80.85	312.5	283.448	813.821	79.994	5.3103	.1877
5.6	82.32	313.8	284.726	812.839	80.077	5.1725	.1909
5.7	83.79	315.0	285.984	811.870	80.159	5.1341	.1941
5.8	85.26	316.2	287.242	810.902	80.242	5.0508	.1973
5.9	86.73	317.4	288.466	809.962	80.321	4.9707	.2005
6.0	88.20	318.6	289.688	809.023	80.401	4.8922	.2037
6.1	89.67	319.8	290.893	808.097	80.478	4.8169	.2069
6.2	91.14	320.9	292.059	807.199	80.555	4.7448	.2101
6.3	92.61	322.0	293.247	806.288	80.629	4.6727	.2133
6.4	94.08	323.2	294.395	805.406	80.705	4.6038	.2164
6.5	95.55	324.3	295.526	804.537	80.777	4.5382	.2196
6.6	97.02	325.4	296.658	803.669	80.849	4.4725	.2228
6.7	98.49	326.4	297.770	802.814	80.921	4.4100	.2259
6.8	99.96	327.5	298.885	801.961	80.989	4.3491	.2291
6.9	101.43	328.5	299.961	801.135	81.058	4.2899	.2323
7.0	102.90	329.6	301.037	800.309	81.126	4.2322	.2354
7.25	106.575	332.1	303.692	798.273	81.292	4.0944	.2433
7.50	110.250	334.6	306.256	796.307	81.450	3.9647	.2512
7.75	113.925	337.1	308.763	794.385	81.607	3.8445	.2590
8.00	117.600	339.4	311.198	792.520	81.756	3.7308	.2668
8.25	121.275	341.7	313.598	790.684	81.902	3.6251	.2747
8.50	124.950	344.0	315.925	788.904	82.040	3.5242	.2825
8.75	128.625	346.2	318.195	787.167	82.177	3.4296	.2903
9.00	132.300	348.4	320.431	785.459	82.309	3.3399	.2980
9.25	135.975	350.5	322.610	783.792	82.436	3.2534	.3058
9.50	139.650	352.5	324.734	782.170	82.562	3.1733	.3135
9.75	143.325	354.6	326.842	780.561	82.683	3.0965	.3213
10.00	147.000	356.6	328.894	778.995	82.802	3.0228	.3290
10.25	150.675	358.5	330.890	777.470	82.915	2.9539	.3367
10.50	154.350	360.4	332.869	775.962	83.029	2.8866	.3444
10.75	158.025	362.3	334.809	774.481	83.140	2.8241	.3521
11.00	161.700	364.1	336.717	773.028	83.245	2.7633	.3598
11.25	165.375	365.9	338.603	771.590	83.351	2.7056	.3675
11.50	169.050	367.7	340.436	770.195	83.452	2.6495	.3751
11.75	172.725	369.4	342.250	768.814	83.551	2.5967	.3828
12.00	176.400	371.2	344.027	767.462	83.648	2.5454	.3904
12.25	180.075	372.8	345.787	766.123	83.743	2.4957	.3981
12.50	183.750	374.5	347.508	764.813	83.837	2.4493	.4057
12.75	187.425	376.1	349.213	763.555	83.927	2.4028	.4133
13.00	191.100	377.8	350.899	762.237	84.017	2.3596	.4209
13.25	194.775	379.4	352.548	760.984	84.103	2.3179	.4285
13.50	198.450	380.9	354.179	759.744	84.190	2.2763	.4361
13.75	202.125	382.5	355.792	758.520	84.272	2.2378	.4437
14.00	205.800	384.0	357.367	757.325	84.355	2.1994	.4512

temperature of vaporization will evidently be q , and r being the latent internal heat of 1 lb. of vapor, $x r$ will be the latent internal heat of the quantity of vapor x ; hence the total heat in the mixture will be—

$$Q_1 = q + r x$$

the quantities q and r being found from the table.

The usual method of determining the total heat of wet steam has been to regard the total *latent* heat of the vapor as contained in the steam, and to employ the formula—

$$\begin{aligned} Q_1 &= N q + N_1 L \\ &= N (t - 32^\circ) + N_1 (1091.7 + 0.305 (t - 32^\circ)) \end{aligned}$$

N being the number of lbs. of water, and N_1 the number of lbs. of vapor in the mixture; the specific heat of water being 1, and the initial temperature being 32° .

The difference between this formula and the last, from which we have—

$$(N + N_1) Q_1 = (N + N_1) (q + r x)$$

being that the *internal latent heat* of the vapor, only, is considered, $N + N_1$ being the total weight of liquid and vapor.

134. The values of $q = q + r + \frac{P U}{772}$ found from the tables,

conform to the law of Regnault, that the total heat increases uniformly as the temperature rises.

The amount of this increase is small even for a great range of temperature. For instance, the total heat necessary to raise a lb. of water from 32° to 212° , and evaporate it at that temperature, is 1146.6 units of heat; and the quantity necessary to raise the same amount of water from 32° to 329.5° Fahr. (corresponding to 7 atmospheres), and evaporate it at that temperature, is only 1182.47, or 35.9 additional units of heat; less than $\frac{1}{25}$ part of the latent heat of evaporation of 1 lb. of water at 212° .

The values of z , the latent heat of evaporation, may be found from the table, for any given pressure or temperature, by adding

together the corresponding values of r and $\frac{P U}{772}$.

DENSITY OF GASES AND VAPORS.

135. The term density refers to the degree of approximation of the particles of a body to each other. It becomes specific when it refers to the number of molecules or atoms in a unit of volume of a given substance, this unit being a standard for all bodies. In English measures, one cubic foot is the standard unit of volume, and the weight of a cubic foot of a substance in any condition is the *specific weight* of that substance in that condition. It is usual to express specific weights in terms of the weight of a unit of volume of a standard substance, the latter weight being taken as unity. Water is the general standard for specific weights, but for gases and vapors air is also taken as a standard, the weight of one cubic foot of air being unity.

The following table shows the relative densities at 32° Fahr. and one atmosphere pressure, of some of the gases commonly met with :

XVI. Relative Densities.

Air	1.00000	Water.....	1.0000000
Nitrogen	0.97137	Air.....	0.0012932
Hydrogen	0.06926	Nitrogen.....	0.0012562
Oxygen.....	1.10563	Hydrogen.....	0.0000896
Carbonic Acid....	1.52901	Oxygen.....	0.0014298
		Carbonic Acid..	0.0019774

136. The following are the *weights* of one cubic foot of each of the same substances in pounds avoirdupois, under the same conditions, viz., at 32° F. and one atmosphere pressure, except for water, which is taken at 39.1° Fahr. :

XVII. Weight in pounds Avoirdupois of 1 cu. foot.

Water	62.425
Air.....	0.08073
Nitrogen.....	0.07860
Hydrogen.....	0.00559
Oxygen.....	0.08926
Carbonic Acid.....	0.12344
Steam	0.0502

137. The density of a perfect gas, at any other pressure and temperature, may be found from the law of Mariotte and Gay-Lussac.

In the expression

$$P V = R T$$

v may be taken as the *volume of unit of weight* or *specific volume*, and if d represent the weight of unit of volume or

specific weight, we shall have $v D = 1$ and $v = \frac{1}{D}$

hence

$$\frac{P}{D} = R T$$

and for any other pressure and temperature $\frac{P_1}{D_1} = R T_1$

From these two equations we obtain by division—

$$\frac{P}{P_1} \frac{D_1}{D} = \frac{T}{T_1}$$

and

$$D_1 = D \frac{P}{P_1} \frac{T}{T_1}$$

The density here considered, being the *specific weight*, or weight of a unit of volume, may be found in the above table, headed, *weight in pounds avoirdupois of one cubic foot*, for any perfect gas mentioned in the table.

138. The *specific volume* of a gas is the volume of unit of weight. In English measures *one pound avoirdupois* is the unit of weight, and to obtain the specific volume we have $v = \frac{1}{D}$ the reciprocal of the *specific weight*.

Specific volumes, or *volumes of one pound of each of the substances named*, are given below in cubic feet, for 32° Fahr. and one atmosphere :

Air	12.3870
Nitrogen	12.7226
Hydrogen	178.8909
Oxygen	11.2032
Carb. Acid	8.1011
Steam	19.9203

139. If saturated vapors could be treated as perfect gases, the following formulas for determining the specific volumes and specific weights of the vapor of water might be employed :

$$P V = R T$$

in which, for English measures, p is the pressure in pounds per square foot, v the volume of one pound; R is a constant equal to 85.766, and T the absolute temperature. The constant 85.766 is derived from the corresponding value of R for air, on the supposition that the weight of 1 cubic foot of saturated steam is 0.622 that of air at the same temperature and pressure.

From the above formula we have for saturated steam—

$$p v = 85.766 \times T$$

$$v = \frac{85.766 \times T}{p}$$

$$D = \frac{1}{v} = \frac{p}{85.766 \times T}$$

Let it be required, for instance, to determine the volume of 1 pound of saturated steam at a pressure of 6 atmospheres. This pressure corresponds to a temperature Fahr. of 318.6, and the corresponding *absolute* temperature will be $459.4 + 318.6 = 778^\circ$ Fahr. Six atmospheres pressure is 12700.8 pounds per square foot, and the formula becomes, for the specific volume,

$$v = \frac{85.766 \times 778}{12700.8} = 5.253 \text{ cu. feet,}$$

and for the specific weight,

$$D = \frac{12700.8}{85.766 \times 778} = 0.1903 \text{ lbs.}$$

It has been remarked, however, that for saturated vapors the law of Mariotte is strictly applicable only on the supposition that the vapor is in the superheated condition.

In order that this law may be applicable, it is necessary that the specific weight of vapor shall bear a constant ratio to that of air at the same pressure and temperature. This ratio, as determined by Regnault for saturated steam, is 0.622. The following table gives the ratios of the weights of unit of volume of the vapor of water, relative to air, for increasing pressures, as determined by Zeuner theoretically:

Pressure of the saturated vapor in atmospheres.	Density of vapor relative to air.
0.1.....	0.621
0.5.....	0.633
1.	0.640
2.	0.648
5.	0.662
10.	0.676

From this table it will be seen that it is only at *very low pressures* that the law of Mariotte and Gay-Lussac will apply to saturated vapors. For pressures such as are ordinarily employed in the steam-engine the law does not apply.

140. A knowledge of the *specific volumes* and *specific weights* of saturated vapors, especially of the vapor of water, is of great importance, in technical applications, for the pressures and temperatures usually employed; and until the direct experiments of Fairbairn and Tate were made to determine these quantities, reliance was placed, to a great extent, on the law of Mariotte and Gay-Lussac. These experiments indicated a different law, and one which corresponds perfectly with the dynamic theory of heat.

141. The quantity $\frac{p}{772} u$ in Table XV. furnishes the means of ascertaining directly the specific volume—the column headed u giving the volume of the saturated vapor from 1 lb. of water for different temperatures and pressures. Strictly speaking, the values of u in this table designate the difference between the volume of the vapor of 1 lb. of water and the volume of the water from which it was produced; or,

$$u = u_1 - v_1$$

u_1 being the *real* specific volume of the vapor, and v_1 the volume of one pound of water.

From which we have the real specific volume

$$u_1 = u + v_1$$

v_1 , the volume of 1 lb. of water, which may be regarded as constant for all temperatures, is .016 of a cubic foot, and hence

$$u_1 = u + 0.016 \text{ cubic feet}$$

the value of u being taken from Table XV.

The specific weight will then be

$$D = \frac{1}{u + v_1}$$

The values of the specific weights of the vapor of water calculated in this manner, are found in the table in the column headed D .

These numbers will be found to correspond closely with those of Fairbairn in Table VIII. of his "Mills and Millwork," for the same temperature—Fairbairn's table having been constructed from formulas based on his experiments.

142. Prof. Zeuner gives an empirical formula for D , which is as follows:

$$D = a p^{\frac{1}{n}}$$

in which D is expressed in kilogrammes $a = 0.6061$ and $\frac{1}{n} = 0.9393$.

Referring to the example which has just been given, the volume v of 1 lb. of saturated steam at the pressure of 6 atmospheres is, from the table,

$$N_1 = N + v_1 = 4.8922 + 0.16 = 4.908 \text{ cubic feet.}$$

The value calculated by Mariotte and Gay-Lussac's law, D being 0.622 of air, is 5.266 cubic feet.

The value of D by Zeuner's table is 0.2037 lbs.

The value calculated by Mariotte's law, 0.1903 lbs.

It appears evident that if Mariotte and Gay-Lussac's law is to be applied to saturated vapors, the relative density of steam is not to be regarded as constant, but as varying according to the preceding table, page 70.

If, in the example given, the density of the steam be taken at 0.662, the density of air at 6 atmospheres, the application of this law will give

$$P v = 80.470 \text{ T.}$$

and

$$v = 4.929 \text{ cubic feet.}$$

$$v = 4.908 \text{ by the table.}$$

$$D = .2025 \text{ by the formula above.}$$

$$D = .2037 \text{ by the tables.}$$

Fairbairn gives a formula for what he calls the "specific

volume," equivalent to the following, p being expressed in lbs. per square inch :

$$v = 25.62 + \frac{24317.5}{p + 0.365}$$

This volume, however, is the *ratio* of the volume of the liquid to the volume of vapor that it will produce at the pressure p .* A table of these ratios for different pressures may be found in Fairbairn's work.

Zeuner's tables of specific volumes and specific weights are theoretical, being based on the dynamic theory of heat, and Regnault's tables for temperatures and pressures, while Fairbairn's tables for the same quantities are based on his direct experiments.

To find the *real* specific volume from that designated by Fairbairn as the "specific volume," it is only necessary to multiply the "specific volumes" of his table by 0.016, the volume of one pound of water.



CHAPTER II.

COMBUSTION.

143. CHEMICAL action when accompanied by the development of light and heat is usually called *combustion*.

144. *Inflammation* denotes that kind of combustion in which the products are gaseous and flame is produced.

145. *Ignition* is simply the incandescence of a body unattended by chemical change.*

146. The phenomena of heat being those of rapid molecular motions, the heat and light developed by combustion must indicate an increased molecular movement in the particles of bodies, when combustion takes place, proportional to the amount or force of the chemical attractions.

147. The heat of combustion may therefore be rationally explained by saying that intense and violent increase of motion in the particles of the compound is produced by the chemical attractions.

148. Ordinary combustion consists in the combination of oxygen with various substances: the temperature required being different for different substances, and varying for the same substance with the rapidity of the combustion. Phosphorus combines slowly with oxygen at 77° F.; charcoal burns *slowly*, but does not ignite, below a red-heat; sulphur burns in air at about 550° F.

But most elementary substances require to be heated to redness before combustion in oxygen or the air takes place. According to Peclèt, solids emit light, or become dull red, at about 750° F.

149. "Compression of air does not appear to facilitate combustion unless the combustion takes place rapidly," † and is consequently attended with considerable evolution of heat.

150. Most substances burn with great rapidity when in a

* Watts's Dic. of Chemistry.

† Ibid.

finely-divided state. Fine dust of many substances burns in this manner with a rapidity which, in a closed space, may give rise to such a degree of pressure, from the expansion of the gases, as to produce phenomena like explosions. A single spark may thus produce instantaneous combustion in a space filled with fine dust.

151. Spontaneous Combustion.—Porous substances often absorb and condense air within their pores; oxidation begins, accompanied by an elevation of temperature, which accelerates the oxidation until the process produces spontaneous combustion. Charcoal powder, masses of tow, cotton, or rags, saturated with oil, sawdust mixed with oil, moist hay, and other substances in similar conditions, have thus been known to burst into flame.

Wood does not take fire in oxygen gas, according to Thénard, at temperatures below about 600° F.; but if it be long exposed to a high temperature, even lower than this, in air, it may become partially charred, and rendered so inflammable as to favor the conditions of spontaneous combustion. Under such conditions, a single spark, or accidental exposure of the substance to a higher degree of heat, may cause it to take fire.

Charcoal from wood made at a temperature of 480° F. takes fire in air when heated to about 650° Fahr.

152. Ordinary combustion is accompanied, usually, by *incandescence* and flame. If a solid burns without flame, the heat evolved at the surface of contact of the air and the solid causes an elevation of temperature of the residual solid particles, which gives rise to a *glow*, or *incandescence*, the color and intensity of the light being dependent on the temperature. Dull red indicates the lowest temperature at which light appears, and dazzling white, the highest degrees of heat; between these extremes the light passes from dull red, or cherry red, to bright red, dull white, then to a yellowish and finally to a bluish white, and a full or dazzling white.

If the combustible is gaseous, the combination with oxygen may be instantaneous, producing by the violent concussion of the air an explosion. In order that the phenomenon of explosion may take place, the combustible gas must be mixed uniformly with air, or oxygen, in the proper proportions, and then heated to the burning-point. A similar effect takes place when a solid combustible, such as sulphur or charcoal, is mixed with

a *nitrate* or other solid which gives up its oxygen readily. In both cases it is only necessary that the temperature be raised to ignition at one point by friction, percussion, or the contact of a hot body, the action being then propagated instantaneously throughout the whole mass.

When the combustion is gradual, the contact of the combustible gas with oxygen, or the air, takes place usually at the bounding surface of the gas; as, for instance, when a jet of gas issues from an orifice, or when a column of gas rises from the wick of a candle. The inner mass of the combustible gas does not ignite at first, and the ignited surface assumes the form of a hollow cylinder, or cone.

153. The brightness and color of such a flame depend not only on the degree of temperature, but upon the presence of solid incandescent particles in the flame. These solid particles arise sometimes from the compound produced by the combination, but in ordinary forms of combustion of fuel they are particles of carbon. Hydrogen gas, carbonic oxide, alcohol, and sometimes coal-gas, burn thus with a dull flame.

A bright flame is produced by compounds which contain carbon, from which a portion of the carbon becomes separated by the heat produced; the separated particles being first heated to incandescence, and afterwards burned by contact with the air. If the quantity of air supplied be not sufficient, these solid particles may become cooled and form soot. The visible part of smoke is this soot cooled below red-heat.

Marsh-gas, olefant gas, ether, volatile oils, resins, fats, etc., when burned, give off carbon in this manner, and may form bright flames, or produce, if the separated particles are not all burned, soot, or smoke.

154. *A purely gaseous substance does not become luminous at any degree of temperature however high; luminosity being caused by particles of incandescent solids in the gas.*

The combustible ingredients of ordinary fuel, and of the liquids and gases usually employed for the generation of heat, are *carbon* and *hydrogen*. These substances combine readily with oxygen, the former producing by the combination carbonic acid, or carbonic oxide, and the latter water. The oxygen required is usually supplied by the atmosphere, which contains about one-fifth of its weight of this substance.

155. As a general rule, all chemical *combinations* produce

heat, while chemical *decompositions* cause a disappearance of heat. In the combination of two simple isolated elements heat is evolved only, but where the combination is effected through the simultaneous decomposition of compound substances, the heat evolved is the resultant of that which is produced by the combination of the combustible elements, and that which *disappears* through the decompositions.

In compounds containing oxygen and hydrogen in the proper proportions to form water, the surplus hydrogen only contributes to the development of heat, when combustion takes place.

These elements combine to form water in the proportion, by weight, of one part of hydrogen to eight parts of oxygen, and by volume, one of hydrogen to one-half of oxygen.

Carbon unites with oxygen in two proportions, viz. : to form carbonic acid, six parts of carbon to sixteen of oxygen, by weight; and to form carbonic oxide, six of carbon to eight of oxygen. Carbonic oxide is a highly combustible gas, taking up when exposed to air or oxygen, at the proper temperature, eight additional parts, or one equivalent of oxygen to form carbonic acid.

Carbon *completely burned* thus produces carbonic acid and satisfies the conditions of perfect combustion. Imperfectly burned, the result usually of a deficiency of air, it produces carbonic oxide.

156. Composition of Atmospheric Air.—Air is composed of oxygen and nitrogen. Ordinary atmospheric air contains also, mechanically, watery vapor, and carbonic acid in small quantities. Of these elements the oxygen alone is the active agent of combustion.

Pure dry air contains oxygen and nitrogen in the proportion by weight of—

* Oxygen.....	0.236
Nitrogen.....	0.764
	<hr/>
	1.000

and by volume—

Oxygen.....	0.213
Nitrogen.....	0.787
	<hr/>
	1.000

The weight of a given quantity of air is thus 4.25 times the weight of oxygen it contains, and 1.31 times the weight of nitrogen. The volume of a given quantity of air is 4.69 times the volume of oxygen it contains, and 1.27 times the volume of nitrogen.

One pound of carbon to form carbonic acid unites with 2.66 pounds of oxygen, the resultant weight being 3.66 pounds of carbonic acid. This requires 11.3 pounds of air, and produces, after combustion, 12.3 pounds. Since one pound of air occupies at 32° F. and at the ordinary pressure 14.7 pounds per square inch, 12.39 cubic feet, it follows that one pound of carbon requires, for its combustion, approximately, $12.39 \times 11.3 = 140$ cubic feet of air.

One pound of carbon to form carbonic oxide unites with 1.33 pounds of oxygen, making 2.33 pounds of carbonic oxide. This requires 5.65 pounds, or about 70 cubic feet, of air at ordinary temperatures and pressures.

One pound of hydrogen, to form water, requires 8 pounds of oxygen, the resultant being 9 pounds of water. This requires, when the combustion is in air, 33.97 pounds, or 420.0 cubic feet of air, and the total weight after combustion is 34.97 pounds.

One pound of light carburetted hydrogen, or marsh-gas, to form carbonic acid and water, requires 4 pounds of oxygen, the resultant being 5 pounds of carbonic acid and water in the proportion of 1 water to 2.44 carbonic acid. For this combustion 17 pounds, or approximately 210.0 cubic feet of air are required, making 18 pounds of gas and watery vapor after combustion.

For burning one lb. of olefiant gas, 3.43 lbs. of oxygen are required, making 4.43 lbs. of carbonic acid and water; the volume of air required being approximately 170 cubic feet.

157. The *chemical equivalent* of a substance, in chemistry, is a number which designates the proportions by weight in which that substance combines chemically with others; the quantity of that substance in any compound being either in simple or multiple proportion of its chemical equivalent.

158. The *atomic formula* of a substance designates the number of chemical equivalents of the substance or substances which compose it. For instance, the atomic formula of hydrogen being H, and its chemical equivalent being 1, and the

atomic formula of carbon being C, and its chemical equivalent being 6, when these substances unite to form marsh-gas the proportion in which they combine is known to be $C^2 H^4$, *i.e.*, two equivalents by weight of carbon and four equivalents of hydrogen, or $6 + 6 + 1 + 1 + 1 + 1 = 16$. So that the atomic formula of marsh-gas is $C^2 H^4$, and its chemical equivalent 16.

159. The following table gives the atomic formulas, the chemical equivalents, the weight of oxygen, and the weight of the products of combustion in oxygen of the substances named, the atomic formula of oxygen being O, and its equivalent being 8 :

TABLE XVIII.

Table showing the atomic formulas, chemical equivalents, and products of combustion in pure oxygen, of the substances named in the first column.

Name of Combustible.	Atomic Formula.	Chemical Equivalent.	Products of Combustion.	Atomic Formula.	Chemical Equivalent.	Weight of Fixed Oxygen.	Weight of Oxygen per lb. of Combustible.	Weight of Products of Combustion in Oxygen.
Carbon.....	C	6	Carb. Acid	CO^2	22	16	2.66	3.66
Carbon.....	C	6	Carb. Ox..	CO	14	8	1.33	2.33
Carb. Oxide	CO	14	Carb. Acid	CO^2	22	8	0.57	1.57
Hydrogen...	H	1	Water.....	HO	9	8	8.00	9.00
Marsh-Gas..	$C^2 H^4$	16	Carb. Acid	$2CO^2$	44			
			Water.....	4HO		64	4.00	5.00
Olefiant Gas	$C^4 H^4$	28	Carb. Acid	$4CO^2$	88			
			Water.....	4HO		96	3.43	4.43

160. When the combustion takes place in air, the weight of the products of combustion depend on the quantity of air required in each case. The following table gives a recapitulation of the statements already made in general terms for the combustion of 1 lb. of the different substances :

TABLE XIX.

Table showing the products of combustion of 1 lb. of the substances named, in air.

Name of Combustible.	Products of Combustion.	Weight of fixed Oxygen in lbs.	Weight of the Products of Combustion in Oxygen in lbs.	Weight of Air Corresponding in lbs.	Weight of Products of Combustion in Air in lbs.
Carbon.....	Carbonic Acid...	2.66	3.66	11.29	12.29
Carbon.....	Carbonic Oxide..	1.33	2.33	5.65	6.65
Carbonic Oxide..	Carbonic Acid...	0.57	1.57	2.42	3.42
Hydrogen.....	Water	8.00	9.00	33.97	34.97
Marsh-Gas	Carbonic Acid and Water	4.00	5.00	16.99	17.99
Olefiant Gas.....	Carbonic Acid and Water	3.43	4.43	14.57	15.57

161. Most of the substances involved in ordinary combustion are found only in the gaseous state, and at the moment of combination it is supposed that all, even carbon, becomes gaseous. It is hence convenient and often necessary to know the proportions *by volume* in which combinations take place.

162. It is a general principle of chemistry that perfect gases, at a given pressure and temperature, combine in simple numerical proportions by volume: the chemical equivalents being proportional to the densities or multiples of the densities.

The following table exhibits the products of combustion by volume of one volume (1 cubic foot) of each of the combustibles named, and also in exact figures the number of cubic feet of air necessary to burn 1 lb. of each of the substances to form the products specified :

TABLE XX.

Table of the products of combustion by volume of one volume of the various combustibles named.

Name of Combustible.	Composition by Volume of one Volume.	Products of Combustion.	Composition by Volume of Products of Combustion.	Total Volume of Products of Combustion in Air.	Volume of Air required to burn 1 lb. of Comb., in cu. ft.	Volume of Air Corresponding.	Volume of fixed Oxygen.	Volume of the Products of Combustion.
Carbon.....	C	Carb. Acid.	$2(\frac{1}{2}\text{C} + \text{O})$	137.50	137.50	9.39	2.0	2
Carbon.....	C	Carb. Ox..	$2(\frac{1}{2}\text{C} + \frac{1}{2}\text{O})$	83.28	68.66	4.69	1.0	2
Carb. Oxide..	$\frac{1}{2}\text{C} + \frac{1}{2}\text{O}$	Carb. Acid.	$1(\frac{1}{2}\text{C} + \text{O})$	36.14	29.80	2.35	0.5	1
Hydrogen...	H	Water	$1(\text{H} + \frac{1}{2}\text{O})$	509.1	419.7	2.35	0.5	1
Marsh-Gas..	$\frac{1}{2}\text{C} + 2\text{H}$	Carb. Acid.	$1(\frac{1}{2}\text{C} + \text{O})$					
		Water	$2(\text{H} + \frac{1}{2}\text{O})$	228.3	206.4	9.39	2.0	3
Olefiant Gas	$\text{C} + 2\text{H}$	Carb. Acid.	$2(\frac{1}{2}\text{C} + \text{O})$					
		Water.....	$2(\text{H} + \frac{1}{2}\text{O})$	188.5	176.6	14.08	3.0	4

The last column shows the total volume of the gaseous products of combustion in air. The numbers in this column are found in the following manner: For the combustion to form carbonic acid 2 cubic feet of oxygen combine with 1 cubic foot of carbon to form 2 cubic feet of carbonic acid. The volume of the carbonic acid after the combustion will be the same as the volume of the fixed oxygen, and after the combustion, the volume of the products remains the same as the volume of air required for combustion.

In the combustion of carbon to form carbonic oxide, however, it will be observed that for each cubic foot of oxygen used, two cubic feet of carbonic oxide are produced. The amount of air necessary to burn 1 lb. of carbon to form carbonic oxide is given in the table 68.66 cubic feet, which contains $\frac{68.66}{4.694} = 14.62$ cubic feet of oxygen. Each cubic foot of oxygen with the carbon forms two cubic feet of carbonic oxide; so that if we add one cubic foot for each cubic foot of oxygen to the amount of air required (68.66 cubic feet), we shall obtain the total gaseous product, 83.28 cubic feet.

In the combustion of hydrogen the same ratio is observed. In the combustion of marsh-gas one cubic foot is to be added for every two cubic feet of oxygen; and for olefiant gas, one cubic foot for every three cubic feet of oxygen.

These tables are valuable in determining the quantity of gas that is discharged from furnaces, and also in the discussion of problems relating to draft, and the quantity of heat transferred to water in the generation of steam.

In regard to the vapor of water, if it be cooled to the point of condensation, its volume will practically disappear from the volume of products of combustion, causing a considerable reduction of volume in the case of the hydro-carbons, and making the volume of the gaseous products even less than that of the air introduced.

163. Heat Evolved in Chemical Combination.—An important consequence of the dynamic law of heat, and one which has been experimentally verified, is, that all chemical changes are accompanied by corresponding changes of heat. *Chemical action and heat are mutually convertible*; and although the quantity of heat evolved, or annihilated, in any chemical change

can only be experimentally determined, yet it has been established that the *combination of any two bodies, chemically, is attended by the evolution of a quantity of heat equal to that which disappears in their separation.*

164. The quantities of heat evolved or disengaged in chemical combinations are found experimentally by means of *calorimeters*. These measurers of heat are employed in various forms, and operate, generally, in such a manner as to exhibit the effects of the heat evolved in acting on a given substance, such as the melting of ice or the raising of the temperature of a given quantity of water; the quantities of heat being thus indirectly measured by being transferred to some body in which these effects can be estimated in units of heat.

The following table gives, in English units, the quantities of heat disengaged by the combustion of the bodies named, by oxygen:

TABLE XXI.

Names of Combustibles.	Heat evolved by the combustion of 1 lb. of combustible.	Names of Observers.
Hydrogen.....	62.000	Favre and Silberman.
Carbon.....	14.544	"
Graphite.....	14.035	"
Native Sulphur.....	3.966	"
Carbon to Carbonic Oxide.....	4.466	"
Carbonic Oxide to Carbonic Acid.	4.325	"
Marsh-Gas.....	23.513	"
Olefiant Gas.....	21.344	"
Turpentine.....	19.533	"
Alcohol.....	12.931	"
Ether.....	16.250	"
Spermaceti.....	18.616	"
Anthracite of Pennsylvania.....	14.114 (calculated).	Morin and Tresca.
" of Mayenne.....	15.689	"
Bituminous Coals (mean).....	14.400	"
Lignites (mean).....	12.240	"
Peat.....	9.000	"
Peat, 20 per cent. water.....	7.200	"
Coke.....	12.600	"
Dry Wood.....	7.200	"
Wood containing 20 water.....	5.600	"
Ordinary Illuminating Gas.....	18.000	"
Gas from Iron-furnaces.....	1.620	"
Petroleum.....	21.000	"

In this manner the heat evolved in the combination of both simple and compound bodies has been determined by many ob-

servers, especial authority being given to those of Favre and Silberman. In the chemical changes which compound bodies undergo, it may be stated, as a general law, that the heat which appears or disappears is the resultant of the action of the simple elements, and where a compound consists of *combustible* elements only, like *carbon*, and hydrogen, *the heat disengaged is the sum of the quantities of heat disengaged by the combustion of the elements separately.*

This law, though not indisputably established, is considered sufficiently exact for all ordinary purposes.

The *temperature* at which bodies combine, although affecting the rapidity or energy of chemical action, does not affect the *total* quantities of heat involved in the change.

CHAPTER III.

FUEL.

165. FROM the preceding chapter it appears that combustibles employed for the purpose of generating heat may be used in all three states of aggregation, solid, liquid, and gaseous, and that the heat disengaged in the combustion of one pound of combustible is greater for some gases and liquids than for any solid combustible.

166. The question of utility, or value, of a combustible, depends, however, largely on other considerations than its heat-producing power. The only liquid that is found in abundance in nature, which might be employed as a fuel, is petroleum, and the cost of this liquid, combined with characteristics which make it difficult and unsafe for transportation in large quantities as fuel, renders it unfit and unprofitable in most cases, except for producing light. It is only in exceptional circumstances that it is employed in the generation of steam. Its chemical composition is, according to Tate, nearly identical with that of oil of turpentine, viz.: equal equivalents of carbon and hydrogen, and its calorific power estimated to be 21,000 English units.

For transportation safely in large quantities air-tight metallic vessels are necessary. It gives off, at ordinary temperatures, vapors, which, if they become mixed with air in suitable proportions in enclosed spaces, form a dangerous explosive mixture. Atmospheric air mechanically charged with the *liquid* hydrocarbons is employed to some extent both for heating and lighting purposes. The heating power of such a saturated air is considered to be about the same as that of illuminating gas. A peculiar property of this mixture is that a portion, at least, if not all, of the oxygen necessary for combustion is contained in the mixture. The liquid hydrocarbons, as is well known, may be produced by the distillation of the bituminous coals.

167. Combustible gases are also found in some localities

under such conditions that they are collected and burned directly from their natural reservoirs; but for universal use they are produced by distillation of the coals.

Ordinary illuminating gas is not only employed for lighting, but for heating purposes, and is also, to some extent, burned directly in the cylinders of engines to furnish motive power. Its composition varies with the kind and quality of coal used in distillation. A mean or average composition from the French coals is given by Morin and Tresca, as follows, reduced to English units:

TABLE XXII.

One cubic foot contains of		Weight of one cubic foot in pounds.	Weight of each in one cubic foot.	Weight of each in one pound.
Marsh-gas.....	0.59	0.0454	0.0268	0.612
Olefiant gas.....	0.09	0.0795	0.0072	0.164
Carbonic oxide....	0.07	0.0788	0.0055	0.126
Hydrogen.....	0.21	0.0056	0.0012	0.027
Nitrogen....	0.04	0.0786	0.0031	0.071
	<hr/> 1.00	<hr/>	<hr/> 0.0438	<hr/> 1.000

From the above table it appears that the weight of one cubic foot of illuminating gas is 0.0438 pounds, and the volume of one pound $\frac{1}{0.0438}$; or 22.83 cubic feet, at the temperature and pressure at which the standard volumes are estimated. All the gases, except nitrogen, which enter into the composition of this illuminating gas are combustible.

The table on page 85, also from Morin and Tresca's work, gives the products of combustion of illuminating gas in English measures, and also the volumes of air necessary to burn one cubic foot.

In the combustion of illuminating gas the volume of the products of combustion is essentially the sum of the primitive volumes of the air necessary for combustion, and the volume of the gas; for example, 1 cubic foot of gas requires 7.462 cubic feet of air, and the volume of the products is 8.462 cubic feet.

In cases where the vapor of water and carbonic acid, or either of these products, is condensed to the liquid form, there will be a considerable reduction in volume. For watery vapor this condensation may easily be effected by cooling; and for the carbonic acid, by the absorption of the acid by alkaline solutions. If the vapor of water alone is condensed, the reduction of volume of the products will be about two-tenths; if both

the carbonic acid and the water are condensed, the reduction of volume will be three-tenths; the combustion in both cases being in air.

The gases which are evolved when bituminous coal, wood, or peat is heated, are composed of carbonic oxide and hydro-carbons; these gases are produced in all furnaces in which these combustibles are employed, and the supply of air and the management of the furnaces should be such as to completely burn the gaseous products; otherwise they may pass through the chimney unconsumed, involving not only a loss of heat, but producing smoke and soot.

TABLE XXIII.

Combustion of Illuminating Gas.

Composition of one cubic foot of the gas.	Products of combustion.	Volume of carbonic acid.	Volume of water.	Volume of nitrogen.	Total volume of products.	Volume of fixed oxygen.	Volume of air corresponding.
Marsh-gas. 0.59	Carbonic acid. 0.59 ($\frac{1}{2}C + O$) Water. 0.59 $\times 2(H + \frac{1}{2}O)$	0.59	1.18		0.59 1.18	0.59 0.59	2.769 2.769
Olefiant gas. 0.09	Carbonic acid. 0.09 $\times 2(\frac{1}{2}C + O)$ Water. 0.09 $\times 2(H + \frac{1}{2}O)$	0.18	0.18		0.18 0.18	0.18 0.09	0.845 0.422
Carbonic oxide. 0.07	Carbonic acid. 0.07 ($\frac{1}{2}C + O$)	0.07			0.07	0.035	0.164
Hydrogen. 0.21	Water. 0.21 ($H + \frac{1}{2}O$)		0.21		0.21	0.015	0.493
Nitrogen. 0.07	Nitrogen. 0.04 N.			0.04	0.04		
1.00 cubic foot.		0.84	1.57	0.04	2.45	1.59	7.462

168. **Natural Solid Combustibles** may be arranged under the following designations :

Anthracite Coal.
Bituminous Coal.
Lignite.
Peat.
Wood.



A classification which represents, generally, the geological occurrence of the vegetation from which the fuel has been produced.

169. **Charcoal** and **Coke** are to some extent artificial combustibles, the former being produced by the carbonization of wood or peat, and the latter by the carbonization of bituminous coal. In both cases the volatile matters of the wood or coal are driven off by heat, leaving a residuum which is composed principally of carbon and fixed inorganic matters.

170. **Artificial Solid Combustibles** composed of coal-dust, used tanbark, and other refuse combustible matters, are made to a considerable extent in France and other parts of Europe, in order to utilize what would otherwise be wasted materials. The dust or other refuse matter is mixed with a small quantity of clay, and sometimes a small quantity of bituminous matter is added to facilitate combustion. The mixture, compressed into the form of bricks, has the property of burning slowly without being easily extinguished, and giving out a regular and continuous heat.

Large establishments in France, Belgium, and Germany are devoted to the manufacture of these artificial combustibles, the bricks being formed under powerful hydraulic pressure where the combustible is designed for portable engines, though often submitted to the natural drying action of the air, where the fuel is intended for domestic use.

Morin and Tresca give the following composition for some of these artificial combustibles, viz.: 80 to 85 per cent. of carbon, 4 to 5 of hydrogen, about 5 per cent. of volatile products, and 5 to 8 per cent. of ashes.

171. **Properties of Anthracite.**—This combustible stands first in value, at least in this country, as a fuel, containing as it does the largest proportion of pure carbon, the element on which the industrial and commercial values of a given fuel most depend.

The American anthracites are not generally subject to the objection found to the use of the English and French anthracites, of decrepitating, or breaking up into small fragments, during combustion, and are therefore available for nearly all purposes in the generation of heat, whether in domestic use, the generation of steam, or in metallurgical operations.

This combustible is not easily ignited, and is readily extinguished if the supply of air is not kept up, rendering the

management of the combustion difficult. It is not easily broken, and may therefore be transported without great loss from the accumulation of dust.

172. Bituminous Coals.—The bituminous coals are most universally distributed, and constitute the real basis of industrial enterprise and progress.

The varieties of coal in this class are so great that it is difficult to establish a distinction between some of the semi-bituminous coals and anthracite on one side, and bituminous coals and the lignites on the other. The bituminous coals are distinguished by the presence of more or less volatile matters (hydro-carbons) which are given off on the application of heat. In ordinary combustion in air, these volatile matters form a large volume of combustible gas above the fuel during the first stages of the combustion, which constitutes a considerable part of the fuel, and usually burns with considerable flame. If the combustion of these gaseous matters is not complete, particles of pure carbon are set free and form smoke or soot.

The prevention of smoke from bituminous coal has always been found a difficult problem; a sufficient supply of air properly mingled with the gases, and a high temperature at the same time, for ignition and combustion, are the elements which must be combined to make the combustion complete.

The bituminous coals of England are divided into *caking* and *non-caking* coals, which correspond to the American designations *caking* and *free-burning* coals. The free-burning or non-caking coals are those in which the lumps or pieces retain to a great extent their original forms, leaving the interspaces free for the circulation of air. The caking coals are those which, during combustion, assume to a certain extent a pasty, glutinous form, the lumps sticking together in such a manner as to prevent the circulation of air in the mass. This property is valuable in some metallurgical operations where air is supplied to the interior of the fire by a powerful blast; but in others, especially in the generation of steam, where it is important to utilize as much as possible the external radiant heat of the fire, and where a free circulation of air throughout the mass is indispensable, the caking coals are objectionable.

In both anthracite and bituminous coals, inorganic substances occur, which often modify greatly their value. This inorganic matter is derived in part from the vegetable tissues from which.

the coal is produced, but largely also from the earthy matters in the strata deposited with the coal. The admixture of seams of slate or shale in lumps of coal is not uncommon; but such imperfections can generally be detected by superficial observation. The quantity of ashes is generally the only evidence of the amount of inorganic matter, and to some extent is an index of the value of the coal. The proportion of ashes may be so great as materially to impair the quality of the coal. From one to four per cent. of ashes is the ordinary amount in the best coals, though in some valuable coals the proportion of ashes is much larger, amounting in some instances to over ten per cent. The ashes are often of such a nature that they fuse or melt, and form masses of clinker; and when this takes place to any considerable extent, the coal is inferior for use in steam-boilers. The clinker, if not repeatedly removed, impairs the circulation of air, and may adhere to the grate-bars, thus causing their destruction. The presence of earthy matters in connection with clinker is still more injurious.

Nearly all bituminous coal contains iron pyrites, the oxidation of which may produce spontaneous combustion; and when this substance exists in considerable quantities in coal, especial watchfulness is necessary when the coal is stored in confined places, such as the coal-bunkers on steamships. Iron pyrites also assists the fusion of the ashes and the formation of clinker. Bituminous coal usually contains 65 to 85 per cent. of carbon, about 6 per cent. of hydrogen, 5 to 6 per cent. of volatile matters, and 3 to 6 per cent. of inorganic matter.

173. Lignites.—The lignites, which approach in composition and geological age the bituminous coals, differ from them only in degree, being generally inferior, though often fit for use as fuel. The more recent lignites, which preserve the structure of the vegetable tissues, are seldom used. Where other fuel is scarce these lignites may take the place of wood, being intermediate in properties and value between wood and coal. They generally contain a large amount of water.

174. Peat.—This combustible differs from lignite in presenting a peculiar spongy appearance, resulting from the vegetable tissues from which it is produced. It is apparently composed of the debris of plants and grasses which have grown during the present geological epoch upon the sites of what are now recognized as peat-beds. It contains a large amount of water, and is

usually prepared by drying in the sun and open air. Used in this state, which involves little expense in preparation, it may be obtained at so low a price as to make it profitable as a fuel, even on railways. It is composed, according to the determinations of Regnault, whose analyses for other combustibles have been approximately given above, of about 60 per cent. of carbon, 5 per cent. of hydrogen, about 30 per cent. of oxygen and nitrogen, and 5 to 8 per cent. inorganic matter. Its calorific power, in proportion to its bulk in the crude state, is small, and many attempts have been made to condense it by mechanical pressure. In Germany this combustible is employed to a considerable extent for locomotives, in both the crude and compressed states. Charcoal from peat is employed in metallurgical operations, but is too costly for ordinary purposes in the generation of steam.

175. Wood.—In localities where the removal of the primitive forests is the first necessary step to the cultivation of land, the use of wood for the generation of steam for manufacturing purposes, and for the purposes of transportation, is economical; and in such localities it is the principal source of fuel. But the secondary growth of forest-trees, as countries become settled, is too much needed for necessary domestic uses, and for timber, to be employed extensively in the production of steam. The exceptions to this general rule are those cases where the refuse pieces of timber, sawdust, and shavings which accumulate in manufacturing establishments, are thus utilized as fuel.

The value of wood as a fuel depends greatly on its dryness. According to the analysis of M. Baer, given by Morin and Tresca, all the common woods, whether hard or soft, have nearly the same general composition, containing about 50 per cent. of carbon, 6 per cent. of hydrogen, 43 to 45 of oxygen, and less than 1 per cent. of ashes.

The proportion of oxygen by weight is, according to this analysis, about seven times that of the hydrogen, or nearly sufficient for the combustion of all the hydrogen present; so that it may be said that all wood contains about 50 per cent. of carbon and about 1 per cent. of free hydrogen.

Wood contains also, mechanically, a large proportion of water. After two years of natural "seasoning" it is found to contain about 20 per cent., and sometimes 30 per cent., of water, the efficacy of the seasoning depending on the condition of the wood, whether split, sawed, or left in the round state in which it grows.

When subjected to distillation or heating, by which the volatile matters are driven off, the products are a residue of about 15 per cent. of carbon, 85 of volatile matters, hydro-carbons, and other gaseous products, and less than $\frac{1}{2}$ per cent. of ashes.

In employing wood for heating purposes it is important, therefore, as in the case of bituminous coal, to provide for the combustion of the escaping gases.

The calorific power of dry wood is about 7,200 English units of heat for the combustion of 1 lb., and for wood containing 20 per cent. of water, 6,400 units of heat.

176. Wood-Charcoal.—This combustible is produced by the heating of wood, without access of air, until the volatile matters are driven off and a residue of carbon and a small quantity of volatile matter remains. The lowest temperature at which this occurs is about 400° Fahr., but a red-heat is indispensable for complete carbonization.

The volatile matters driven off consist of water, acetic acid, tar, and other condensable matters, and the permanent gases, carbonic acid, carbonic oxide, hydrogen, and carburetted hydrogen.

The quality of the charcoal varies to some extent with the temperature of carbonization. It is stated by Percy that charcoal made at about 260° C. burns most easily, but that made at 1,000° and 1,500° C. cannot be ignited like ordinary charcoal.

“Charcoal, made at a constant temperature of 300° C., takes fire in air when heated to 360° and 380° C. Charcoal made between 260° and 280° C. ignites between 340° C. and 360° C. That made between 290° C. and 350° C. ignites between 360° C. and 370° C. That made at 432° C. burns at about 400° C., and that made between 1,000° C. and 1,500° C. burns between 600° and 800° C.” *

The composition of charcoal varies somewhat with the wood from which it is produced, and especially with the temperature of carbonization; but of the ordinary kinds the composition given by various analyses is approximately as follows:

Water.....	6	to	8	per cent.
Carbon.....	85	to	89	“
Hydrogen.....	2	to	3	“
Oxygen.....	1	to	3	“
Ashes.....	1.5	to	3	“

* Percy's *Metallurgy*.

The higher the temperature of carbonization the greater will be the proportion of pure carbon, and the less the proportion of oxygen, hydrogen, and nitrogen.

Charcoal absorbs water rapidly, the commercial charcoal generally containing 10 to 12 per cent. of moisture. In the state of powder this absorption is increased, and it is less for charcoals produced at higher temperatures than for low temperatures.

It is evident from the above that charcoal must be an expensive fuel for the purposes of generating steam, because a large part of the combustible matter of the wood is driven off, and, unless utilized, is wasted. The cost of this combustible is thus an objection to its general use for generating steam, except in exceptional cases.

177. **Coke** is obtained from the distillation of bituminous coal by processes analogous to those employed in the preparation of charcoal; the quality of the coke depending greatly on the coals from which it is derived, and also on the process of coking. Ordinary coke contains about 90 per cent. of carbon, 6 per cent. of ash, and 3 to 4 per cent. of oxygen, hydrogen, and nitrogen. It absorbs water rapidly, and hence should not be left exposed to the weather. Immersed in water, it may absorb as much as 30 to 50 per cent. of its weight of water. Before being burnt, therefore, it should be dried by exposure in dry air, if it has been long subjected to conditions favorable to the absorption of moisture.

Coke was formerly almost exclusively used in France and England for locomotives, principally on account of its intrinsic value as a fuel, as it makes a steady, constant fire, and burns without smoke.

Gas-cokes, which are extensively used in cities for domestic fuel, contain less carbon, and more of inorganic matter producing ashes, than the cokes prepared for locomotives and for metallurgical operations; the composition of gas-coke, according to Morin and Tresca, being about 60 per cent. of carbon, 8 to 20 of hydrogen, and 20 to 30 of ashes.

The use of coke as a fuel for the generation of steam is, as in the case of charcoal, restricted by its cost. It is only where the volatile products of the distillation are utilized, as in the manufacture of illuminating gas, that the residual coke can be sold at a price which renders it advantageous for the generation of steam.

178. The kind or quality of fuel to be employed in the generation of steam for industrial or commercial purposes, is often determined by local or other conditions, independent of the special characteristics of the fuel. In nearly all cases the element of cost is the controlling one, account being taken of all the conditions essential to economy. Where the question of choice of fuel for a special purpose is to be decided, all these conditions are to be considered in connection with the quality of the fuel.

Professor Walter N. Johnson, in his report to the Navy Department, in 1844, on "American coals applicable to steam navigation and to other purposes," establishes ten "ranks," as follows. Names of coals arranged in the order of

1. Their relative weights.
2. Rapidity of ignition.
3. Completeness of combustion.
4. Evaporative power under equal weights.
5. Evaporative power under equal bulks.
6. Evaporative power of combustible matter.
7. Freedom from waste in burning.
8. Freedom from tendency to form clinker.
9. Maximum evaporative power under equal bulks.
10. Maximum rapidity of combustion.

It was found impossible to select any one coal which could be considered first in all these qualities; and it is not even possible to attach equal importance to all the ranks. For different purposes the relative values of the different qualities must be differently estimated.

For the purposes of steam navigation he attaches the most importance to the fifth rank, "the evaporative power under equal bulks," because stowage-room occupied by the fuel is an important feature in steam navigation.

With the fifth rank he combines the eighth and tenth, viz., "freedom from clinker" and "maximum rapidity of action." According to this report the American coals are generally superior to, or at least not surpassed by, the foreign coals, in all the most desirable qualities for producing steam.

In regard to the use of coke, peat dried in the open air, and wood, it is stated by Peclèt that experiments made in Austria

demonstrated that one pound of coke is equivalent to 2.25 pounds of peat, and to about 0.11 of a cubic foot of pine or 0.09 of a cubic foot of oak wood.

179. The following useful table is taken from the work of Morin and Tresca, the quantities being converted from French to English units. It gives the constitution, calorific power, quantity of air necessary for combustion, and volume of the products of combustion, for the various combustibles employed in industrial operations, the quantities being average or mean values for the combustibles employed in Europe.

TABLE XXIV.

Table showing the composition and calorific power of various combustibles, the quantity of oxygen and air necessary for combustion, and the volume of the products of combustion of 1 lb. of combustible.

Name of Combustible.	Composition.				Calorific Power.	Weight of Oxygen necessary for Combustion.	Weight of Air necessary for Combustion.	Volume of Air corresponding, cu. feet.	Volume of Products, cu. feet.
	C.	H.	Volatile Matter.	Ashes.					
Carbon.....	1.00	.....	.....	.....	14,400	2.66	11.29	137.6	137.6
Anthracite Coal.	0.90	0.03	0.03	0.04	13,500	2.64	11.21	138.9	136.2
Bituminous Coal	0.85	0.05	0.06	0.06	14,400	2.66	11.29	139.6	140.1
Lignite.....	0.70	0.05	0.20	0.05	11,700	2.26	9.69	120.2	116.3
Peat.....	0.55	0.05	0.30	0.10	9,000	1.86	7.90	97.9	102.1
Peat 0.20 Water.	0.39	0.04	0.50	0.07	7,200	1.49	6.32	78.3	81.5
Coke.....	0.85	0.05	.....	0.10	12,600	2.26	9.69	120.2	116.9
Peat-Charcoal ..	0.82	.....	.....	0.18	9,000	2.18	9.25	114.5	112.7
Dry Wood.....	0.48	0.06	0.05	0.01	7,200	1.75	7.43	91.9	89.2
Wood 0.20 Water	0.40	0.05	0.25	0.01	5,400	1.40	5.94	73.5	71.8
Wood-Charcoal ..	0.80	.....	0.04	0.07	10,800	1.86	7.90	97.9	96.3
Hydrogen.....	.....	1.00	.....	.....	52,200	8.00	33.97	420.6	475.4
Carbonic Oxide	0.43	.....	0.57	.....	4,320	0.57	2.42	29.9	35.6
Illuminating Gas	0.62	0.21	0.17	.....	18,000	2.64	11.22	136.3	176.7
Gas from Blast Furnaces.....	0.06	0.02	0.92	.....	1,620	0.23	0.99	12.2	30.3

Mean composition of combustibles, exclusive of ash; according to Percy.

	Carbon.	Hydrogen.	Oxygen.
Wood.....	49.21	6.27	44.52
Peat.....	54.25	6.4	39.35
Bituminous Coal.....	82.59	5.08	12.33
Anthracite.....	94.03	2.94	3.03

CHAPTER IV.

THE TRANSFER OF HEAT.

180. THE combustion of bodies in air being to a certain extent a self-sustaining process, it is only necessary to supply the elements of combustion, fuel, and air, in proper proportions, and to ignite the combustible at one point, in order to produce heat at will, and in any desirable quantities. And the elements necessary being almost universally distributed, or at least readily procurable, there are scarcely any circumstances in which the evolution of heat for useful purposes is not practicable.

For the purposes of heat-power it is not practicable, however, except in some *small* heat-engines, to employ the heated products of combustion directly in the cylinders of engines. And hence the necessity of transferring the heat of combustion to water, or some other liquid, in order to make use of the vapor of the liquid as the medium through which the heat is utilized. Watery vapor is that which is universally used, not only on account of the favorable properties of this vapor, but also from the universal distribution and cheapness of the liquid, the expense of procuring it being insignificant.

The apparatus for producing steam under the circumstances required for use, must combine therefore the conditions necessary for the supply of fuel and air, the supply of water, the transfer of the heat of combustion to the water, and the retention of the steam produced.

The full discussion of these conditions in the case of the steam-boiler involves the construction and arrangement of the parts of the boiler, and cannot be disconnected from them; but there are certain general principles of physics which form the basis of such construction and arrangements, which may be first enumerated in a general way, such as the *laws of transfer of heat*, the *temperature of the products of combustion*, and the *laws of conduction*.

181. **The Transfer of Heat** from a heated body to one that is at a lower temperature consists, according to the dynamic

theory of heat, in the loss of living force, due to heat-motion, in the hotter body, and an equivalent gain of living force in the colder body. When the two bodies are quite distinct, or separated, and do not form part of one and the same body, this transfer takes place generally, as has been stated; through the intervening ethereal medium by the process of radiation. Through this medium there is a tendency to equilibrium of temperature, or of living force; the relative exchange of temperatures being inversely proportional to the masses of the bodies.

It is probable that the transfer of heat between two bodies is always thus accomplished by *radiation*, although, technically, a distinction is made between the transfer at appreciable distances, or *radiation*, and the transfer by actual *contact* of the two bodies.

182. Heat may be transferred practically also by the actual change of position of the body in which it exists. In this mode of transfer, which is called *convection*, or carrying, the transfer is a mechanical one, and is not in any way connected with the change of heat in the body carried. Although this mode of transferring heat is of great importance in the arts, and especially in connection with the generation of steam, involving as it does the question of circulation of heated fluids, yet after the convection of heat by the transfer of the body in which it exists, whether that body be solid, liquid, or gaseous, there still must take place the transfer from the heated body to another, by the process of radiation or contact, before the heat can be utilized *as heat*. Thus a heated gas or liquid may be carried through pipes, or may be mingled mechanically with other gases or liquids for the purpose of conveying heat; but the final process by which that heat is actually transferred from the heated gas or liquid to another body, *as heat*, must depend on the dynamic laws of heat.

In adopting, therefore, the usual designations of the modes by which heat is transferred, viz.,

Radiation,
Contact,
Convection,

it is to be understood that the latter is a mechanical mode,

and need be discussed only in connection with the carrying of bodies to the places or points at which it is desirable or necessary for them to impart their heat to other bodies.

183. Radiation of Heat.—A heated particle of a substance communicates vibrations to the ethereal medium, whether the particle be surrounded by air or whether it be in a vacuum. In ordinary language, the particle sends *rays* of heat in every direction; these rays or waves proceed indefinitely, without change in strength or character, and with the same velocity as light, until they are intercepted by some body in the paths of the rays. If such a particle be a *molecule* on the surface of a body, it is evident that it will send off rays of heat in every direction not intercepted by the body itself.

It is a common error to suppose that the intensity of a *ray* of heat diminishes as the distance between the body emitting and the body receiving the heat increases, *i.e.*, inversely as the square of the distance. The same popular error exists to a certain extent in regard to the force of gravitation; whereas the greatest conceivable distances have apparently no effect in retarding or diminishing the effects of the influences called heat and gravitation.

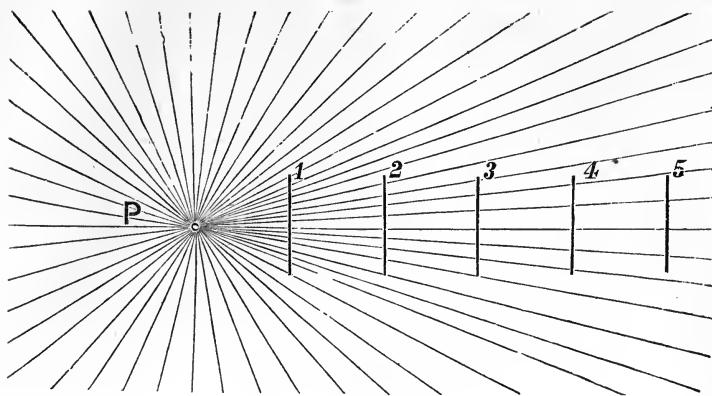
The law of the inverse squares of the distances is rather a geometrical than a physical law, and refers to the action of one *body* on *another*, whether the question be one of heat or gravitation.

A body or collection of molecules possessing a certain amount of living force, due to heat, imparts this energy to the ethereal medium in all directions, and the quantity of energy *intercepted* by another body will depend on the distance between the two bodies; the quantity thus intercepted by the *same body* at *different distances* being inversely proportional to the squares of the distances.

This purely geometrical law may be illustrated by the following sketch:

Suppose r to be a heated body giving off radiant heat in every direction. Another body, a plate for instance, placed at distances 1, 2, 3, 4, 5, ... from the heated body, will intercept less of this heat as it is removed from the heated body, the number of rays, or quantity of heat, intercepted at two different distances being, from the geometrical conditions of the problem, inversely proportional to the squares of those distances.

FIG. 2.



The absurdity of supposing that, because the mathematical result of reducing the distance to zero is a symbol of *infinity*, therefore the physical influence at that distance is *infinite*, need not be discussed, although such an assumption is often made in attempts to discuss the intensity of molecular forces.

When, therefore, it is said that the intensity of radiant heat varies inversely as the square of the distance, all that is meant is, that the *same body*, placed at different distances from the same source of heat, will receive, in a given time, by radiation, different quantities of heat in the inverse proportion of the squares of the distances. In going away from a glowing fire in our grates, for instance, we receive less and less heat, because, as the distance is increased, we pass out of the paths of large numbers of divergent rays which would otherwise reach us.

184. The inclination of the surface which intercepts radiant heat determines, for similar reasons, the quantity of radiant heat received. Even if the rays be supposed parallel, as in the case of the radiant heat of the sun, it is apparent that all the heat conveyed by a beam of rays may be represented by the section of the beam perpendicular to its direction. If the beam falls upon a surface inclined to its direction, the amount of surface over which the beam will be distributed will be greater as the inclination of the surface is greater. If the surface be plane,

when it becomes parallel to the axis of the beam, it will receive no heat.

Hence in estimating the intensity of radiant heat by units of surface, the inclination of the receiving and absorbing surfaces must be considered.

The regions of the earth's surface near the poles, from their approach to parallelism with the direction of the sun's beams, receive little heat on each square mile of surface, compared with the quantity received by a square mile at the tropics.

185. If a heated body be placed within an enclosed space, it is evident that although some parts of the enclosure may receive more heat per square foot than others, yet all the heat emitted will be absorbed.

All the heat emitted by radiation from the incandescent fuel on the grate of the furnace of a steam-boiler is thus absorbed by the side walls and crown of the furnace, though in different proportions per square foot.

186. Attempts have been made to determine the quantity of heat in units of heat emitted by any given surface at a given temperature, supposing the temperature of the absorbing surfaces to remain at constant temperature.

MM. Dulong and Petit, whose researches in this and other branches of physics are universally known, made numerous experiments on this subject, which resulted in the determination of certain general laws. The experiments were made to determine the rate of cooling of bodies in an enclosed space, the space being filled with different gases, and the enclosure being maintained at constant temperature.

The results were enunciated as follows :

1. "The cooling of a body results from radiation and from contact of the fluid or gas which surrounds it.

2. "The rate of cooling, from radiation alone, is the same for all bodies at the same temperature, but its absolute value depends on the nature of the surfaces."

It is represented by the following formula :

$$Q = c \cdot a^t (a^{t_1} - 1) \text{ or } Q = c_1 (a^{t_1} - 1)$$

in which Q represents the number of French units of heat emitted by one unit of surface in a unit of time, c a constant depending on the nature of the surface of the radiant body, a , the

number 1.0077,* t the temperature of the enclosure or absorbant, and t_1 the *excess of temperature* of the radiating body over the absorbing body in degrees Centigrade.

3. "The rate of cooling by *contact* of a fluid surrounding the heated body is also the same for all heated bodies, but its absolute value does not depend on the *nature of the surface*, and depends only on the form of the heated body."†

For air under ordinary atmospheric pressure the law of cooling by contact is expressed by the formula

$$Q = c' t^{1.233}$$

in which Q represents the quantity of heat in calories abstracted from one unit of surface by the air in a unit of time, c' a constant depending on the form of the surface, and t the excess of temperature of the body over that of the air surrounding it.

187. These general laws were confirmed by Peclèt, who made many experiments to determine the constant co-efficients of the formulas. Similar experiments have more recently been made also by Mr. Hopkins, whose results are as follows, for radiation alone :

For Glass.

$$Q = 9.566. a^t (a^{t_1} - 1)$$

Dry Chalk.

$$Q = 8.613 a^t (a^{t_1} - 1)$$

Dry New Red Sandstone.

$$Q = 8.377 a^t (a^{t_1} - 1)$$

Polished Limestone.

$$Q = 9.106 a^t (a^{t_1} - 1)$$

* It was proved by De la Provostaye and Desains that a differs for different bodies.

† Peclèt.

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In which q represents the quantity of heat emitted in one minute from one square foot of surface, in terms of a unit which is the quantity of heat required to raise the temperature of 1,000 grams of water 1° Centigrade.

Mr. Hopkins also determined by experiment the constants in the formula for the cooling power of gases by contact, the results of which, as given below, are also quoted from Balfour Stewart.

For Atmospheric Air.

$$q = .0372 \left(\frac{p}{720} \right)^{.45} t_2^{1.233}$$

For Hydrogen.

$$q = .1288 \left(\frac{p}{720} \right)^{.38} t_2^{1.233}$$

For Carbonic Acid.

$$q = .0359 \left(\frac{p}{720} \right)^{.517} t_2^{1.233}$$

For Olefiant Gas.

$$q = .0497 \left(\frac{p}{720} \right)^{.501} t_2^{1.233}$$

p representing the pressure of the gas in millimetres.

188. In regard to these formulas, it may be doubted whether the experiments were made in such a manner as to lead to results of practical value. The constants determined by Peclèt, and by Hopkins, can only refer to the special conditions under which the experiments were made, which conditions are not those admitting of general application. Moreover, the separating of the influences of radiation and contact in the experiments does not seem to have been sufficiently complete.

189. The only results of value seem to be the general laws, as enunciated, without reference to *quantities of heat*.

The *relative* radiating powers of different surfaces at 180° Fahrenheit, as determined by Leslie, are represented approximately in the following table:*

* Watts's *Dic. of Chemistry*.

Lampblack.....	100	Mica.....	80
Paper.....	98	Graphite.....	75
Resin.....	96	Tarnished lead....	45
Sealing-wax.....	95	Mercury.....	20
Crown glass.....	90	Polished lead.....	19
India ink.....	88	Polished iron.....	15
Ice.....	85	Tin plate.....	12
Red lead.....	80	Gold, silver, copper.	12

Experiments by Magnus give the following relative emissive powers for different surfaces at 270° Fahr. :

Blackened silver.....	100
Glass.....	64
Fluor-spar.....	45.5
Rock salt.....	13
Polished silver.....	9.7

It is stated by Magnus that the greater or lesser density of the surface has no influence on radiation from the surface. Platinum which has been strongly hammered, possesses the same emissive power as platinum carefully annealed. But the same surface roughened with emery-paper has its emissive power greatly increased. As far as quantities of heat are concerned, it is doubtful whether anything further than such *relative* determinations can, in the present state of knowledge, be depended on; the actual or absolute quantities for different temperatures being still uncertain.

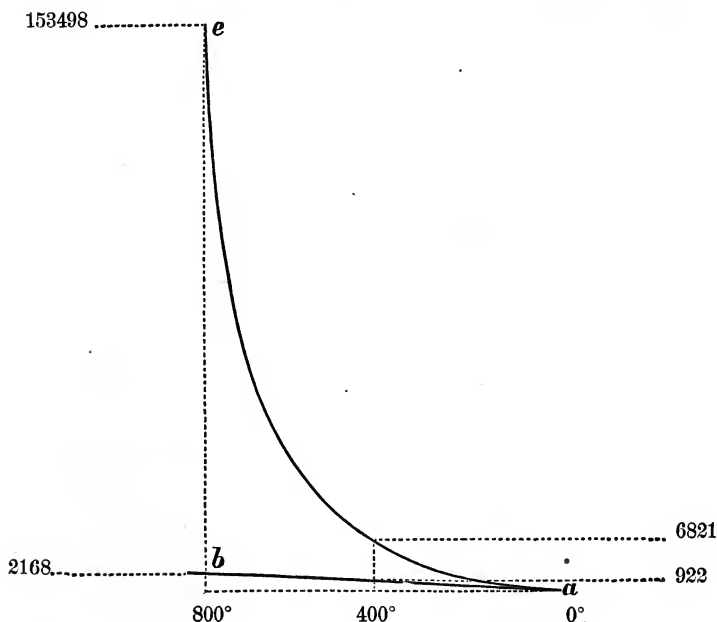
190. The laws of radiation which have been enunciated point out, however, one fact which has an important bearing in connection with the transfer of heat. The formula $q = c \cdot a^t (a_1^t - 1)$ or $c_1 (a_1^t - 1)$ shows that the differences of temperatures of the radiant and absorbing bodies enter as *exponents* in the formula, so that with a constant temperature of the absorbent body, such as the water over the furnace in steam-boilers, the quantity of heat emitted by the grate, and absorbed by the water, will increase with great rapidity as the temperature of the fire increases. The formula for the cooling of the gaseous products of combustion, on the other hand, $q = c' t_1^{1.233}$ shows, if this law be true, that the influence of increase of temperature in the

gases is not so great as in radiation, because the difference of temperature between the heated gases and the water of the boiler is simply raised to the power indicated by the constant exponent 1.233.

191. These formulas serve to illustrate, by curves, the emission of heat, in English units, by radiation and contact of a gas, the absorbent of the heat being maintained at constant temperature, and the temperature of the heated body, whether a radiating solid or a gas, being gradually increased.

Diagram illustrating the emission of heat by radiation and by contact of gases.

FIG. 3.



In the above diagram the lower horizontal line represents differences of temperature, in Fahr. degrees, between the heated gas or radiating body, and the absorbing body. The vertical line *b c* represents English units of heat transferred to an absorbent at constant temperature. The ordinates of the curve *a b* represent heat transferred by contact of gases, according to

the law $Q = c_1 t_1^{1.233}$ and the ordinates of the curve $a c$, the heat transferred by radiation, according to the law $Q_1 = c_1 (a^{t_1} - 1)$. These quantities have been calculated, according to the best data, for the conditions presented in the furnace and flues of a steam-boiler. For small differences of temperature the two curves are nearly identical. For a difference of 400° the heat absorbed by the plates from contact of gases will be, for unit of surface and unit of time, 922, and from radiation 6821. For a difference of temperature of 800° the heat absorbed from contact of the gases in unit of time and for unit of surface, found by calculation, is 2168, and for the same difference of temperature the heat absorbed from radiation is 153498 units.

This application of the laws of Dulong and Petit is made on the supposition that the law of cooling by radiation is the reciprocal of the law of absorption of radiant heat, and the law of cooling by contact of a colder gas is the reciprocal of the law of heating by contact of a hot gas; the *direction* of the transfer of heat being a matter of indifference. The diagram is drawn from a larger one constructed from calculated ordinates, and is given merely to illustrate the great difference between the transfer of heat by *radiation* and contact for large differences of temperature between the heating and absorbing bodies. Thus, according to these calculations, the quantity of heat transferred or absorbed by one square foot of surface from a radiating body, with a difference of temperature of 800° , is over 70 times the quantity absorbed from heated gases in the same time with the same difference. These illustrations are made on the supposition that the difference of temperature remains constant for a given time.

In the radiation of heat, such as the radiation from the heated fuel of a furnace, this constancy of temperature is kept up usually by the progress of the combustion. But in heated gases the constancy of the difference of temperature, or the high temperature of the gas in contact with any given portion of surface, can be maintained only by the removal of the cooled gas and the renewal of heated gas from the furnace.

This involves the question of the circulation of gas and the *convection of heat*—elements of the problem which render the determination of constants for the formulas doubtful.

192. Action of Bodies on Radiant Heat.—Light and radiant heat are now assumed by philosophers to be manifestations of

the same physical agent; and heat, like light, when it falls upon the surface of a body may be reflected, refracted, absorbed, or polarized.

The radiating powers of different bodies, or different surfaces, represent also their absorptive powers, and, as has been already stated, radiant heat does not affect the eye, or solids do not become luminous, until the temperature reaches about 750° Fahr.

193. The radiation and absorption of gases, according to Professor Tyndall, present very peculiar laws, and our knowledge of the action of gaseous bodies on radiant heat is still very slight. It has been demonstrated experimentally by Professor Tyndall that a ray or beam of heat is wholly, or almost wholly, transmitted through moderate distances in air, oxygen, hydrogen, and nitrogen; and conversely, no radiation takes place from the heated particles of these gases. The only mode, therefore, by which heat can be imparted to these gases, or by which they can impart heat to other bodies, is by actual contact.

Some other gases possess remarkable powers in absorbing or intercepting *dark* radiant heat.

194. The absorption of radiant heat by vapor of water diffused in air, under circumstances of average humidity, was shown by Professor Tyndall to be 70 times greater than the absorption by dried air. As the quantity of watery vapor was increased, the amount of heat absorbed was increased.

This fact has been suggested by Mr. C. E. Emery, a practical engineer of N. Y., to be an important cause of loss of heat in the cylinders of steam-engines, when there is condensation in the cylinder. The walls of the cylinder radiate heat to the cloudy vapor and become cooled, the heat radiated being carried out with the exhaust; and when new steam is again admitted the walls are again re-heated by the incoming steam.

Comparative experiments, made with glass and iron cylinders, seemed to confirm this view, glass being a feeble radiator and absorber. Acting on this idea, Mr. Emery proposed a mechanical separator to the double-cylinder engine, to remove the particles of water from the steam in its passage from the smaller to the larger cylinder.

As the quantity of watery vapor contained in air at different temperatures is often a matter of importance in technical applications, and especially when taken in connection with the

radiation of heat, the following table is here introduced, showing the quantities of watery vapor in air at dew-points from 0° to 100° Fahr.:

TABLE XXV.*

Deg. Fahr.	Grains in a cu. foot.	Deg. Fahr.	Grains in a cu. foot.	Deg. Fahr.	Grains in a cu. foot.	Deg. Fahr.	Grains in a cu. foot.	Deg. Fahr.	Grains in a cu. foot.
0	0.186	21	1.618	42	3.274	63	6.400	84	12.079
1	0.810	22	1.674	43	3.382	64	6.620	85	12.439
2	0.836	23	1.733	44	3.495	65	6.810	86	12.808
3	0.864	24	1.793	45	3.610	66	7.024	87	13.185
4	0.893	25	1.855	46	3.729	67	7.243	88	13.577
5	0.925	26	1.915	47	3.851	68	7.469	89	13.977
6	0.957	27	1.986	48	3.979	69	7.702	90	14.387
7	0.992	28	2.054	49	4.109	70	7.941	91	14.809
8	1.028	29	2.125	50	4.244	71	8.186	92	15.241
9	1.065	30	2.197	51	4.382	72	8.439	93	15.684
10	1.103	31	2.273	52	4.524	73	8.699	94	16.140
11	1.143	32	2.350	53	4.671	74	8.966	95	16.607
12	1.184	33	2.430	54	4.822	75	9.241	96	17.086
13	1.226	34	2.513	55	4.978	76	9.523	97	17.577
14	1.270	35	2.598	56	5.138	77	9.813	98	18.081
15	1.315	36	2.686	57	5.303	78	10.111	99	18.598
16	1.361	37	2.776	58	5.473	79	10.417	100	19.129
17	1.409	38	2.870	59	5.648	80	10.732		
18	1.459	39	2.996	60	5.828	81	11.055		
19	1.510	40	3.066	61	6.013	82	11.388		
20	1.563	41	3.168	62	6.024	83	11.729		

195. The fact that air charged with moisture absorbs, in each unit of time, 70 times more heat than air practically dry, is an explanation of a phenomenon which has an important bearing on human health and comfort. When air at a *high temperature* is overloaded with moisture, radiation takes place from the air to the body, producing an oppressive sensation of heat. When, on the other hand, the temperature of saturated air is lower than the natural temperature of the body, the radiation, or transfer of heat, will take place from the body to the air, producing the sensation of cold. It is this that makes a low temperature, with a dry atmosphere, more bearable than a higher temperature with air highly charged with moisture.

196. **Transfer of Heat by Contact.**—This subject has been partially discussed in connection with radiation.

Definite knowledge on this subject, in reference to quantities of heat, would be of greater value, practically, than a knowledge

* Encyclopedia Britannica.

of the exact laws of radiation, because in nearly all cases the quantity of radiating surface, in the evolution of heat by combustion, depends on the quantity of incandescent surface of the fuel, the size of furnace, and form of bed of fuel; which quantities are dependent on the quantity of heat required per hour, and are thus fixed by other conditions than the laws of radiation. But the utilization of the heat in the gaseous products of combustion requires special constructions of flues and pipes which, while conveying these gases to the chimneys, act at the same time as heating surfaces for liquids in contact with the surfaces. When heated gases, or liquids, are conveyed in pipes or conduits to the places where the heat is to be given off by contact or radiation from metallic surfaces, the utilization of heat involves the laws of transfer by contact, and the determination of the necessary amount of surface in such case is often directly dependent on these laws. The quantity of heating surfaces of steam-boilers, the cooling surfaces of condensers, the quantity of surface of hot-water pipes for heating air for dwellings and factories,—questions which are continually presented to the engineer,—are dependent on the action of these surfaces in transferring, by contact, the heat of a liquid or gas on one side of a surface to a liquid or gas on the other side.

197. It may be regarded as a rule that when the liquids or gases on the opposite sides of a metallic plate remain at constant temperatures, respectively, the thickness of the plate does not affect the *rate* of transfer of heat from one side to the other. It is only when the temperatures of the fluids on the opposite sides are changing, that the internal conductivity of the wall between them, or the dissipation of heat by the wall, need be considered.

Thus the influence of the thickness of the metallic flues of a steam-boiler is felt only in retarding the rapidity of first generating steam after the fires are started. After the boiler is “in train,” *i.e.*, working steadily at a given pressure, the greater or lesser thickness of the metallic plates which transmit the heat to the water, is a matter of little importance, as far as the *rate of transfer* is concerned. This fact was experimentally demonstrated by Boutigny, and has been confirmed by the direct observations of others.

198. It is stated by Rankine that the following empirical formula gives, approximately, the rate of transfer of heat per

hour for each square foot of heating surface of the tubes or flues of steam-boilers :

$$Q = \frac{(t_1 - t)^2}{a}$$

in which $t_1 - t$ is the difference of temperature between the heated gases on one side at any point, Q the quantity of heat transferred in units of heat, and a a constant, the value of which lies between 160 and 200.

This formula is intended only as a rough approximation. As it is stated by Rankine to be the results of experiments on the evaporative powers of boilers, it is probably applicable only to the special conditions of those experiments.

If we regard the water in the boiler as the absorbent of the heat—the sides of the flues being the walls of the chambers which separate the water from the heated gases—the application of the law of Dulong and Petit would give the quantity transferred by each square foot in an hour as follows :

$$Q = c. (t_1 - t)^{1.233}$$

differing from Rankine's formula only in the exponent.

All that is known definitely on this subject, at present, appears to be that the transfer is proportional to the difference of temperature raised to a power greater than unity, probably between 1 and 2.

The greatest difficulty in applying either law lies in the indeterminate constant coefficient.

In all cases of heating or cooling a fluid, by contact with a surface, the quantity of heat transferred in a unit of time depends on the circulation of the fluid; and where one fluid is heated or cooled by another, the two fluids being separated by a metallic plate, the circulation of both fluids must be taken into consideration. This is the condition under which the heat of the gaseous products of combustion in the steam-boiler is transferred to the water. Want of circulation in either the heated gases, or the water, causes a retardation or complete suspension of the transfer of heat.

199. When heat is thus transferred by contact from one fluid, either liquid or gaseous, to another, through a metallic plate, it

results, from the law that the quantity transferred depends on the *difference* of temperatures, that the motions of the two fluids should be in opposite directions. The difference of temperatures will then be the greatest possible at every point.

200. *Heating surface* is an expression used to designate, in mechanical constructions, the surfaces or plates, usually metallic, through which heat is transmitted. Where the transfer is by the contact of a fluid, as in the flues of steam-boilers and cooling surfaces of condensers, the heating or cooling fluid is supplied in a continuous current, or stream, through the flues or pipes. In such cases the fluid usually issues from the apparatus at a constant, determinate temperature. This temperature will depend on the initial temperature and the specific heat of the fluid; and the total quantity of heat transferred from or to the fluid, as it passes through the apparatus, will be represented by the following expression:

$$Q_1 = c_1 (t_1 - t) \times w$$

in which Q_1 represents now, not the heat transferred from a particular square foot of surface in a unit of time, but the whole heat abstracted from, or imparted to, the circulating fluid in a unit of time; $t_1 - t$ represents the loss or gain of temperature of this fluid, and w the total weight of the fluid which passes through the apparatus in a unit of time.

The *volume* of fluid which passes through the apparatus will be proportional to the velocity multiplied by the total sectional area of the flues or pipes through which it passes; and since the weight is equal to the volume multiplied by the density, or $w = v D$, it is evident that it will require a much greater volume of a *gas* to impart or abstract a given quantity of heat than a *liquid*.

If a *given quantity* of heat is to be transferred by an apparatus, through the medium of fluid contact, *in a given time*, that quantity being represented by

$$Q_1 = c_1 w (t_1 - t)$$

or,

$$Q_1 = c_1 v D (t_1 - t)$$

It appears, therefore, that the *volume* of the fluid, its *density*,

its *specific heat*, and the *initial* and *final temperatures*, must all be considered.

Where the initial and final temperatures of the circulating fluid are fixed by the conditions of the problem, the quantities to be considered will be the specific heat, the volume, and the density of the fluid.

For given volumes of flow, liquids are, therefore, under such conditions, more efficient than gases in proportion to their greater density.

201. Conduction of Heat.—Conduction of heat refers to the transmission of heat from one part of a continuous and homogeneous body to another part of the same body. When a body is heated at one point, the heat is transmitted with greater or less rapidity throughout the whole mass, depending on the nature of the body and the differences of temperature of the heated part and other parts of the body. If the body is terminated by two parallel surfaces, which are each kept at a constant temperature, there will be a flow of heat, so to speak, at a constant rate, from the hotter surface to the other by conduction.

The *law of conduction* under these circumstances is, that the quantity transmitted for a unit of area perpendicular to the direction of transmission, and per unit of time, is directly proportional to the difference of temperatures of the parallel surfaces, and inversely proportional to the thickness or distance which separates the two surfaces. If t_1 and t represent the temperatures of the two surfaces, and e the distance separating them, the quantity of heat transmitted will be represented algebraically by the formula

$$Q = \frac{c (t_1 - t)}{e}$$

The coefficient c depends on the nature of the body.

When the quantities of heat thus transmitted, for different bodies, across an interval one unit of length in thickness, and for one unit of area and time, are determined, these quantities of heat represent the *relative* conductibilities of the substances, and the numbers thus found, when referred to one as a standard, may be called the *conductivities* of the different substances.

202. The relative conductivities of metals determined by experiments on bars of a given cross-section, the transmission of heat being determined by thermometers placed at different distances in holes drilled in the bars, have been ascertained by different investigators.

The following table of conductivities, from experiments made by MM. Wiedemann and Franz, the temperatures along the bars being determined by a thermo-electric arrangement, is given by Balfour Stewart:

TABLE XXVI.

Name of Metal.	Relative Conductivities	
	In Air.	In Vacuo.
Silver.....	100.	100.
Copper.....	73.6	74.8
Gold.....	53.2	54.8
Brass.....	23.6	24.
Tin.....	14.5	15.4
Iron.....	11.9	10.1
Steel.....	11.6	10.3
Lead.....	8.5	7.9
Platinum.....	8.4	7.4
Palladium.....	6.3	7.3
Bismuth.....	1.8	—

It was found by Professor Forbes that the conductivity diminishes as the temperature of the metal increases. For iron, the diminution of the number representing the conductivity was from 15 to 25 per cent. for an increase of 100° temperature.

It was shown also by Professor Forbes that the same numbers show the relative conductivity for *electricity*.

For the absolute quantities of heat, in thermal units, transmitted, the following table, from Watts's Dic. of Chemistry, gives the most reliable data for a few substances.

In this table the numbers and formulas give the quantities of heat in calories (kilogram-degrees) which will pass through a metallic plate 1 millimetre in thickness and 1 square metre in area, in 1 second, when the temperatures of the two parallel surfaces differ by 1° Centigrade.

TABLE XXVII.

Name of Substance.	Observer.	
	Ängström.	Neumann.
Copper.....	102.7 (1 — 0.003567t)	110.75
Zinc.....		30.70
Brass.....		30.19
Iron.....	19.88 (1 — 0.00479t)	16.37
German Silver.....		10.94
Lead.....	By Peclet.	3.84

The results of Neumann, reduced to English units of heat and English units of area, thickness, and time, will give the approximate numbers in the following table for the quantity of heat transmitted per second, by conduction, through an area of 1 square foot, and a thickness of 1 millimetre, or .0394 of an inch, the difference of temperatures between the parallel faces of the plate being 1° Fahrenheit :

Copper.....	41.2
Zinc.....	11.4
Brass.....	11.2
Iron.....	6.1
German Silver.....	4.1
Lead.....	1.4

The relative *thermal resistance*, or reciprocal of the conductivity, of *liquids*, as determined by Professor Guthrie,* is given in the following table, for the liquids named :

Water.....	1.0
Glycerine.....	3.84
Acetic Acid.....	8.38
Sperm Oil.....	8.85
Alcohol.....	9.09
Oil of Turpentine.....	11.75

The absolute values of the conductivities of liquids are uncertain. It was ascertained by Professor Guthrie, however, that

* Phil. Transactions, 1869.

the conducting power of liquids is greater at high temperatures than at low temperatures. And when there is no convection of heat in liquids, by which heated particles are carried from one point to another, the conducting power of liquids is very small; the conducting power of water being, according to Depretz, only about $\frac{1}{100}$ that of copper.

203. Conduction by Gases.—Gases possess such a feeble power of conduction that they have been regarded as having no conducting power. Experiments by Magnus, and theoretical deductions by Clausius, however, demonstrate that there is a slight power of conduction in perfect gases.

Clausius estimates the conducting power of air to be about $\frac{1}{1400}$ that of lead.

204. Temperature accompanying Combustion.—The caloric *intensity* of combustion, or degree of temperature of the products of combustion, and of the solid incandescent combustible, seems to depend on the rapidity of combustion rather than the quantity of heat evolved. Nearly all writers on the subject have given a method for finding what may be called the theoretical temperature of combustion, by supposing that all the heat evolved is contained in the gaseous products, and calculating the temperature by means of the specific heats, and the weights of the products of combustion, and the heat evolved,—making use of formulas corresponding to that which has already been given, page 10, viz.:

$$Q = W \times C \times F$$

Q representing, in units of heat, the heat evolved, w the weight, and c the specific heat of the gaseous products of combustion, and F the number of degrees rise of temperature.

From this formula we have

$$F = \frac{Q}{C \times W}$$

In the complete combustion of one pound of carbon, for instance, the products are 3.66 pounds of carbonic acid and 8.63 pounds of nitrogen: the specific heat of carbonic acid is 0.2164, and the specific heat of nitrogen 0.2440. The heat evolved is 14,400 English units.

The quantity F will then be, from the above equation,

$$F = \frac{14,400}{3.66 \times 0.2164 + 8.63 \times 0.2440}$$

$$= \frac{14,400}{2.898} = 4969^{\circ} F$$

205. Such determinations, however, have but little practical value for solid combustibles, because the residual incandescent solid gives off rapidly, by radiation, heat which does not pass off with the gases. The amounts of heat thus given off for different solid combustibles in parts of the whole heat evolved are given by Peclèt as follows :

For Coal.....	0.55
Coke.....	0.55
Wood.....	0.29
Charcoal.....	0.55
Peat.....	0.25
Peat-charcoal	0.48

Assuming that one-half the heat evolved by burning one pound of charcoal is given off by radiation, the temperature of the gases found as above would be $\frac{4969^{\circ}}{2} = 2484.5^{\circ} F$.

The quantity of heat radiated from an incandescent combustible depends not only on the temperature of the combustible, but also on the temperature of the absorbent, and the nature of the surfaces. On this account there does not appear to be sufficient ground for ascertaining the temperatures of furnaces, or of the escaping gases by this process. It is well known from common observation that the temperature in ordinary furnaces is greatly increased by a more rapid supply of air ; so that the quantity of heat evolved in a given time, and the temperature, are thus increased.

Chemical action is promoted by high temperatures, and the conditions for increase of temperature, increase of heat evolved in a given time, and rapidity of chemical action, are coincident. Where excessively high temperatures are desirable, as in blast-furnaces, and in melting metals, the substance to be melted is

placed in contact with the fuel, and all external radiation prevented. Under these circumstances air may be supplied in large quantities by artificial draft to the combustible.

In open furnaces, however, where a part of the heat is to be transferred by external radiation as the combustion proceeds, too much air may be hurtful by chilling the combustible and diminishing the activity of the fire. In all cases, complete or perfect combustion requires a fixed quantity of air, any excess being hurtful. The quantity supplied in a unit of time must depend on the surface of the combustible exposed to incandescence or inflammation, and the rapidity of combustion.

Actual observation by a thermometer is therefore the only reliable means of ascertaining the temperatures which accompany combustion. Such observations, for high temperatures, are uncertain and unreliable with any thermometer now known.

In many applications of heat, in the arts, an exact knowledge of the high temperatures employed would be of great value, and a reliable high-temperature thermometer is greatly needed.

206. Application of the Principles of Transfer of Heat to Steam-Boilers.—The quantity of water which a steam-boiler will evaporate in a given time depends, primarily, on the temperatures to which those parts of the plates of the boiler known as heating surfaces are exposed, and to the extent of those surfaces. In the furnace, the crown and side-walls are exposed to the radiant heat of the incandescent fuel, and to the contact of the heated gases. The heating surfaces of the flues are usually exposed to the contact of the heated gases alone.

The temperature of the fuel, and the initial temperature of the heated gases, depend on the intensity of combustion, or the quantity of fuel burned on each square foot of the grate-surface in a unit of time, and also on the kind of combustion that takes place: *perfect* combustion, in this connection, designating that in which no combustible gases or uncombined oxygen escape to the chimney. For the transfer of heat in the furnace by radiation, if G represent the number of square feet of grate-surface, and q the quantity of heat emitted from each square foot in a unit of time, the quantity of heat transferred, according to the laws of Dulong and Petit, will be, in algebraic symbols,

$$Q_1 = q G = c a^t (a^{t_1} - 1)$$

or,

$$Q_1 = c_1 (a^{t_1} - 1)$$

The transfer of heat by contact of the heated gases *in the furnace* will be represented by

$$Q_2 = F c_2 t_1^{1.233}$$

in which F represents the total furnace surface, and the total transfer of heat in the furnace will be—

$$Q_1 + Q_2 = c_1 (a^{t_1} - 1) + F c_2 t_1^{1.233}$$

In this expression, t_1 represents the difference between the temperature of the incandescent fuel and the temperature of the water in the boiler. If t_w represent the temperature of the water in the boiler, the temperature of the gases as they enter the flues will be $t_1 + t_w$. From this initial point, the temperature of the gases will diminish until they leave the heating surfaces in their course to the chimney. The law of this diminution may be thus found: Let q_1 represent the quantity of heat transferred at any point of the heating surface through one square foot, in one unit of time, the difference of temperature at that point being t . The quantity transferred through an element or band of the heating surface represented by ds will be $q_1 ds$.

The reduction of temperature which the gases undergo, in a unit of time, in passing that surface, will be dt , and the quantity of heat lost by the gases will be represented by $c w dt$, c representing the specific heat of the gases, and w the weight of gas which passes the element ds in a unit of time. The quantity of heat transferred to the water must be equal to that lost by the gases, and hence we have—

$$q_1 ds = c w dt$$

$$ds = \frac{c w dt}{q}$$

Substituting for q its value as given by the laws of Dulong and Petit, we have—

$$ds = \frac{c w dt}{c_2 t^{1.233}}$$

Integrating this expression between the limits t_1 , the initial

temperature, t_2 the temperature of the gases as they leave the flues, we have

$$s = \frac{c w (t_1^{.233} - t_2^{.233})}{.233 c_2}$$

from which the value of t_1 may be found.

$$t_1 = \left(\frac{c w t_2^{.233}}{c w - .233 c_2 s} \right)^{\frac{1}{.233}}$$

In this expression s represents the whole heating-surface of the boiler.

This expression is of no special *practical* value, but serves to indicate a mode by which the initial temperatures may be found. The temperature t_2 of the gases as they leave the flues may usually be observed by a common thermometer, and it would only be necessary to make experiments for ascertaining the value of w , and the constants which enter the equation.

If the initial temperature could be observed, or calculated with certainty, the quantity of heat imparted to the water through the heating surfaces of the flues might be found, being represented by

$$Q_s = c w (t_1 - t_2)$$

If the expression $ds = \frac{c w dt}{c_2 t^{1.233}}$ be integrated between the limits t_1 and 0, which supposes that the flues extend far enough to reduce the temperature of the gases to the same temperature as the water, we should obtain equations by which the relations between q and s , and t and s , become known, viz.:

$$t = c_3 \frac{1}{s^{4.3}} \quad q = c_4 \frac{1}{s^{5.3}}$$

c_3 and c_4 being constants, and s being expressed in units of length of the flues, one unit being the length which corresponds to a segment or band of the flue which is equal to one square unit of area.

The corresponding formulas, if we assume with Rankine that $q = A t^2$, will be

$$t = - \frac{A c w}{s}$$

$$q = \frac{A c^2 w^2}{s^2}$$

These formulas show that after the gases enter the flues the temperatures diminish very rapidly, and that the quantity of heat transferred through each square foot of surface diminishes by one formula as the fifth power, and by the other as the square, if the distance from the initial point increases.

The relative efficiency of heating-surfaces in passing towards the chimney may thus be estimated.

Increase of heating-surface should thus be made as near to the furnace as possible, and not by adding length at the extreme end towards the chimney. This is equivalent to diminishing the unit by which s is measured in the preceding formulas rather than to increase the number of larger units.

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CHAPTER V.

STEAM GENERATORS.

207. To whatever use heat is to be applied through the medium of steam, the apparatus for generating and retaining the steam is constructed on the same general principles for all purposes, and is popularly termed a **BOILER**.

It may be described in general terms as a closed metallic vessel, kept partly filled with water, with arrangements for imparting heat to the water by means of the combustion of fuel.

The steam generated is confined in the vessel, above the water, until it is required for use, when it is drawn off through pipes.

If the steam is required as a source of power, it is supplied to another apparatus, called the *steam-engine*, to which the flow of steam from the boiler is controlled by automatic mechanism.

If the heat of the steam be required for other purposes, such as warming apartments, or for heating liquids or other bodies, the flow is generally regulated by hand, or is dependent on the condensation of the steam at the point at which it is utilized.

This metallic vessel; with its compartments and openings, takes the name of boiler in the shops where it is manufactured. But in many classes or forms of boilers the steam-generating apparatus is not complete until the boiler is set up in brick-work, with an external furnace constructed for the combustion of the fuel, and external flues made for conducting the heated gases to the chimney along the sides of the boiler.

In others the boiler is ready for use as it comes from the manufacturer, having within its external shell all these necessary arrangements for combustion and draft. In all cases certain adjuncts and appurtenances are necessary, such as the feed-pump or other means of supplying water, with the necessary pipes and attachments, the safety-valve, the steam and water gauges, and grate-bars for the furnace. So that a com-

plete steam-generating apparatus requires something more than the simple vessel which constitutes its principal and important feature. For the mere exhibition of the principal phenomena connected with the generation of steam, such a vessel of the most simple form and construction might be sufficient.

But, connected with its uses as an instrument of industrial economy in constant use throughout the world, its employment the basis on which rest the most important interests of civilization at the present day, and its construction and applications consuming costly materials, it has become an object deserving and requiring the most thorough and critical study.

208. As the most important and universal use to which steam is applied is the production of power, the primary conditions which steam generators should fulfil are :

1. *Strength to sustain the internal pressures to which they will be subjected.*
2. *Durability.*
3. *Economy, or efficiency, in evaporating qualities.*
4. *Economy of construction in materials and workmanship.*
5. *Adaptation to the particular circumstances of their use.*
6. *To these conditions must be added safety, which depends on form, construction, strength, and qualities of materials, as well as upon management.*

The first condition—strength to sustain the internal pressures—requires the consideration of the materials to be employed, the statical pressures, or strains, to which these materials will be subjected, and the proper forms and devices to resist those strains.

The condition of durability involves the action of these materials, and their preservation under the varying influences of heat, pressure, and the chemical reactions to which they will be subjected in use.

Economy in evaporative qualities calls for such arrangements for the combustion of fuel and the transfer of heat as shall utilize the greatest possible proportion of the heat which is evolved by the combustion of the fuel.

Economy in materials and construction requires the employment of the least amount of costly materials, and the least labor in the construction, that shall be consistent with the other conditions.

Adaptation to various uses gives rise to various forms, in

which the special use controls, or modifies to some extent, some of the other conditions; while safety of life and property demands that strength of parts, quality of materials, excellence of workmanship, and skilful management shall not only meet the requirements of economy, durability, and adaptation, but shall place beyond contingencies, as far as possible, the occurrence of explosions.

As far as they relate to construction alone, the conditions of *economy* and *safety* stand, to a certain extent, in constant antagonism: the least amount of material that will bear the internal pressures being the extreme limit of economy of construction, while a near approach to this limit is always attended by excessive risk. But as true economy includes permanence and durability under continuous use, it may be said that all the essential conditions are involved in *strength*, *economy of construction* and use, *durability*, and *adaptation*.

209. These considerations, applied in practice, with the aid of experiments on the resistance of materials, and a knowledge of the principles of mechanics, the laws of heat, the chemical processes of combustion, and the action of bodies under the influences of heat, have led to certain general rules and principles which to a certain extent have been reduced to form and are general in their application.

In some important features of construction and use, however, there exists still a deficiency in regard to definite rules of practice which may be universally applied, and engineers and manufacturers of boilers are often governed solely, in some of the details of construction, by precedents or observations derived from their individual experiences.

The laws which govern the selection of materials, the resistance of materials to rupture, the forms of construction best suited to sustain strains and involving the least material, the laws which determine the amount of the strains which arise from the elastic force of steam under different temperatures, and the properties of water and steam under changes of heat, are sufficiently well determined.

On the other hand, the determination of the proper dimensions and relative proportions of parts of steam generators—such as the grate-surface, the heating-surface, the draft areas, and the cross-sections and heights of chimneys—which shall give the most economical results in the evaporation of water—

can hardly be said to have been reduced to exact rules, universally accepted and practised.

The processes of combustion and transfer of heat, and the supply of air to the furnaces, are subjects which do not admit, in the present state of knowledge, of exact and positive analysis, and the result of such uncertainties is undoubtedly to cause a great loss of fuel in a large proportion of instances in current applications. Experience and observation under different conditions of use have led, however, to the establishment of certain general rules for dimensions and proportions, which serve to estimate the performance of boilers within practicable limits; and although these rules are different in different countries, and often in different shops or under different engineers, yet when the dimensions of the apparatus are such as to produce a surplus of steam for any purpose, the regulation of the quantity generated and the economy of the process are subject, to some extent, to the control of the engineer or stoker.

210. *Forms of Boilers.*—In regard to forms and adaptation to various uses, the results of experience have been more definite. The designs or forms in general use may be classified under a few types, which serve to illustrate not only general principles of construction, but the adaptability of the various forms to particular circumstances of use.

Considered merely in reference to strength and internal capacity, combined with the least weight of material, the spherical form is that which fulfils the theoretical requirements of strength and safety. This is the form which a gaseous substance, enclosed by an elastic envelope, assumes under the opposing effects of its internal elastic force and a uniform external resisting pressure. A vessel of this form possesses the advantage, in regard to strength, that every point of the shell or external envelope is exposed to a strain of extension. No cross-strain is produced in any part of the material, and no distortion can occur from the internal pressures.

The spherical form is not, however, the best adapted for the application of heat externally, nor is it the form of cheapest construction. Those conditions are obtained by modifying this form and extending it to the cylindrical shape, which gives the same advantages in transforming all the strains into tangential strains, while it permits of the most extensive variety of arrangements for the application of heat. The cylinder, whether it be

used for the exterior shell of the boiler, in which it is subjected to internal pressures, or for the flues or tubes required for the flow of the gases to the chimney, or for the liquid circulation, is the form best adapted for cheapness of construction, strength, permanence of shape under both internal and external pressures, and for the flow of fluids; and it thus forms a basis for nearly all constructions; modifications or departures from this form being adopted only in exceptional cases, such as the boilers of steam-vessels, where the figure of the external shell is often adapted to the position and space available.

211. The various types of steam-generators may be arranged under the following designations:

1. *The Plain Cylinder Boiler.*
2. *The Cylinder-Flue Boiler.*
3. *The Cylinder-Tubular Boiler.*
4. *The Return-Flue Boiler.*
5. *The Return-Tubular Boiler.*
6. *The Water-Tube Boiler.*
7. *The Locomotive Boiler.*
8. *The Sectional Boiler.*

Each of these types appears under various forms, and the modifications often present such peculiar and distinct characteristics that they would scarcely be classed with either of the above-named types. But for a general discussion these forms comprehend the largest proportion of boilers at present in use, or which have been in use during the last quarter of a century.

212. *The Plain Cylinder Boiler*, represented as it comes from the manufacturer's hands in Plate I., page 122*, is a plain cylinder, formed of wrought-iron plates of $\frac{3}{16}$ to $\frac{1}{2}$ inch thickness, according to the size of the boiler, the ends of the cylinder being closed by cast-iron heads, or by wrought-iron plates hammered into the form of a segment of a sphere. The plates forming the body of the cylinder are shaped to a cylindrical form in a cold state by rollers, the sections thus formed being riveted together longitudinally, and afterwards joined end to end.

The cylinder is surmounted at some point by a cylindrical chamber, called the *steam-dome*, or steam-drum, which is closed at the top by a cast or wrought iron head, on which the castings for attaching the steam-pipes and the safety-valve are usually fitted.

This cylindrical structure is called in the shops a boiler, but

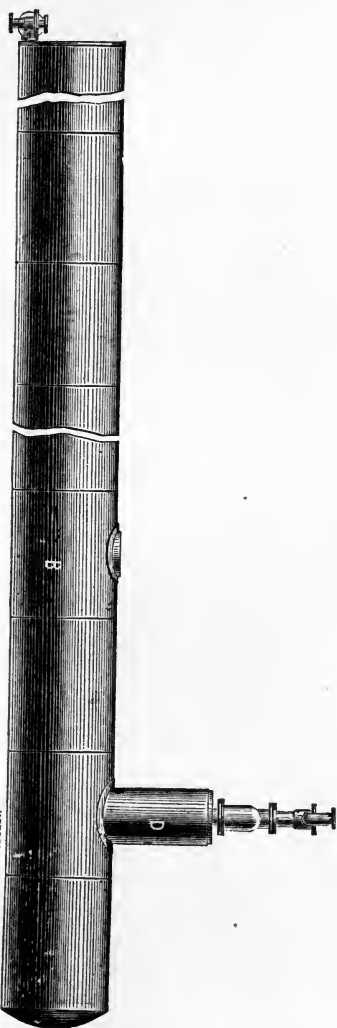
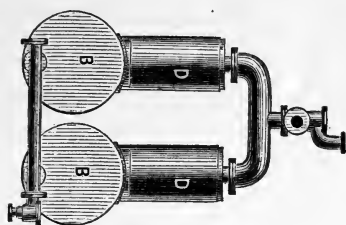
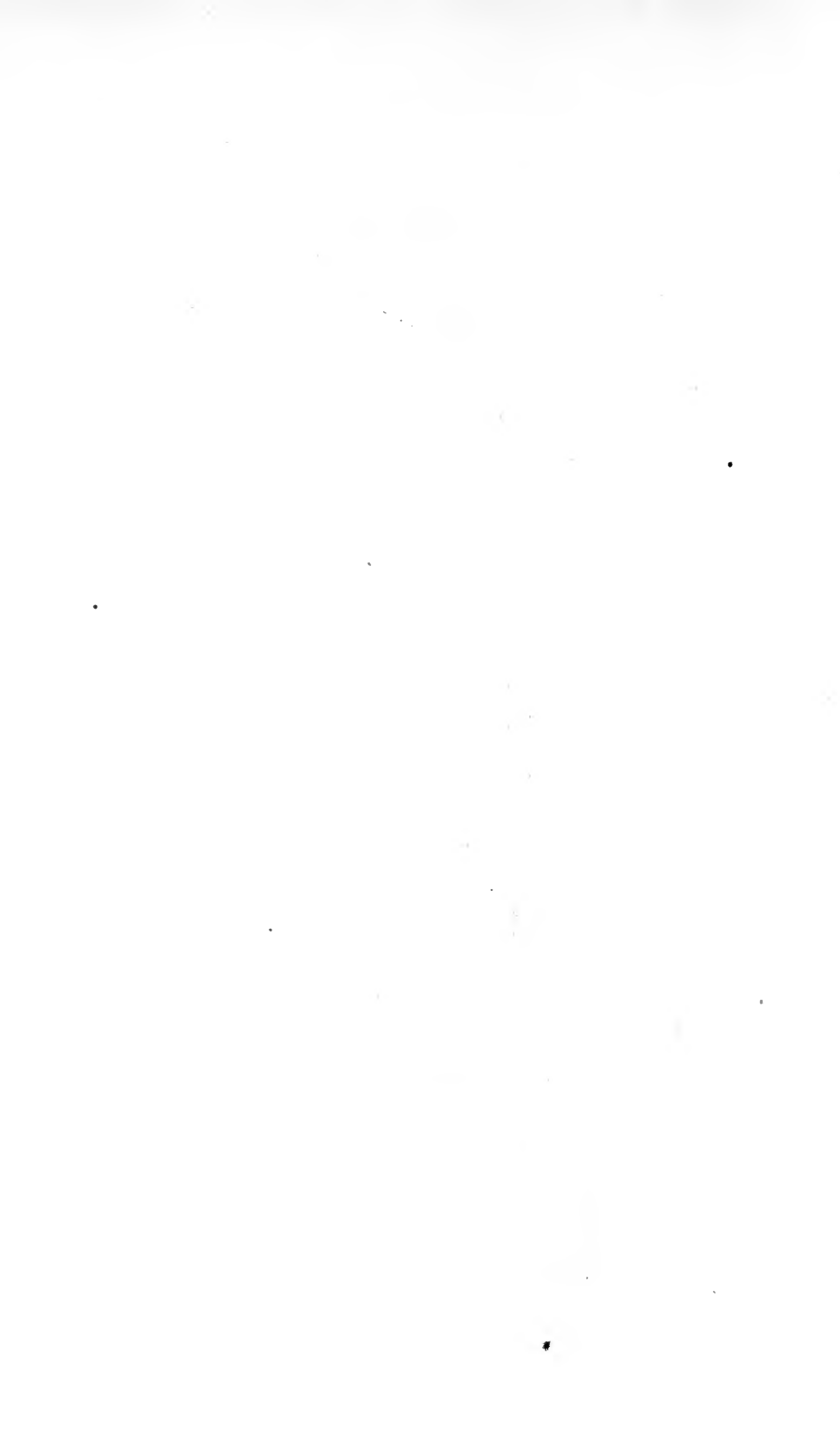
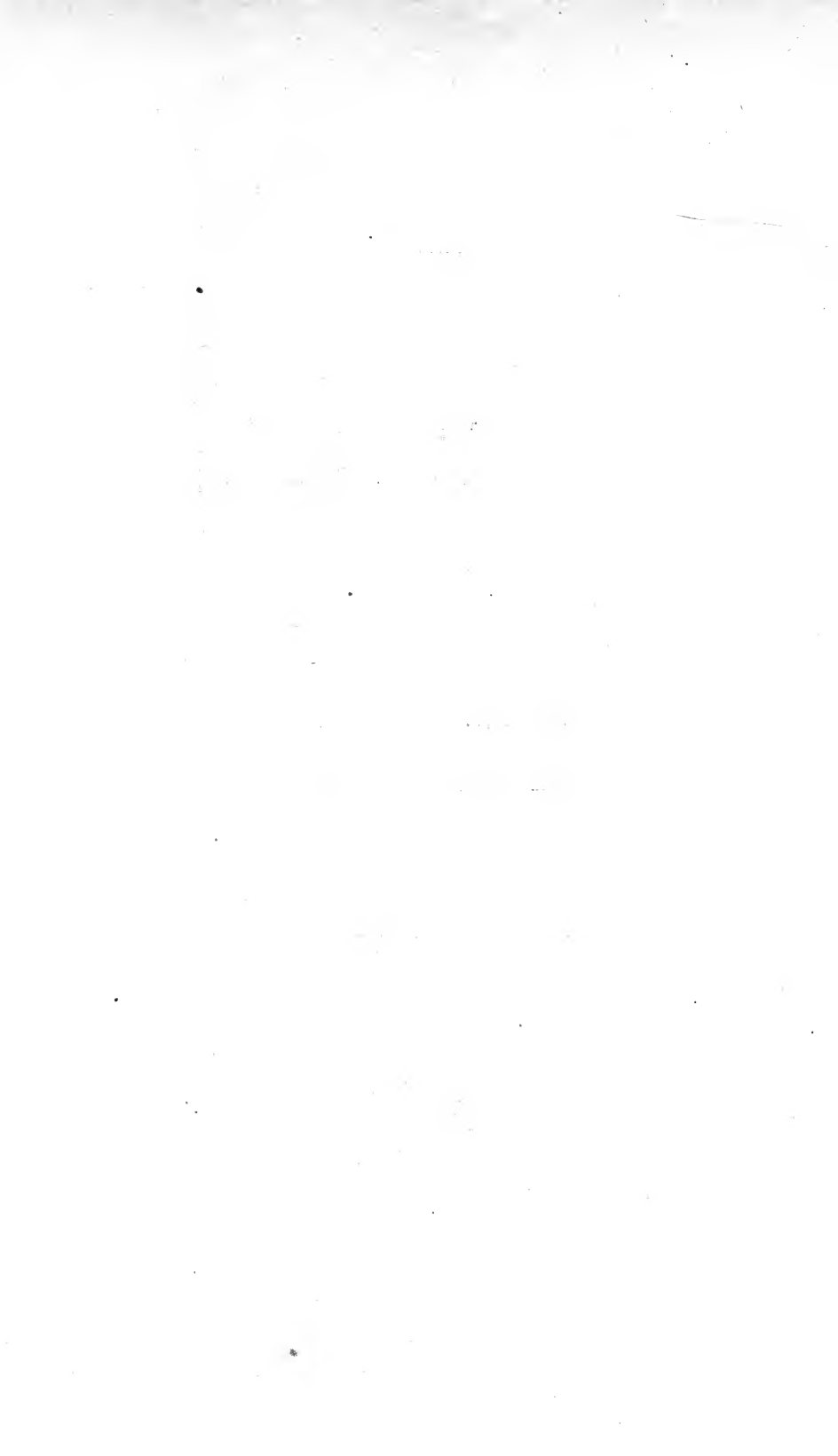


PLATE I.—Plain Cylinder Boiler.





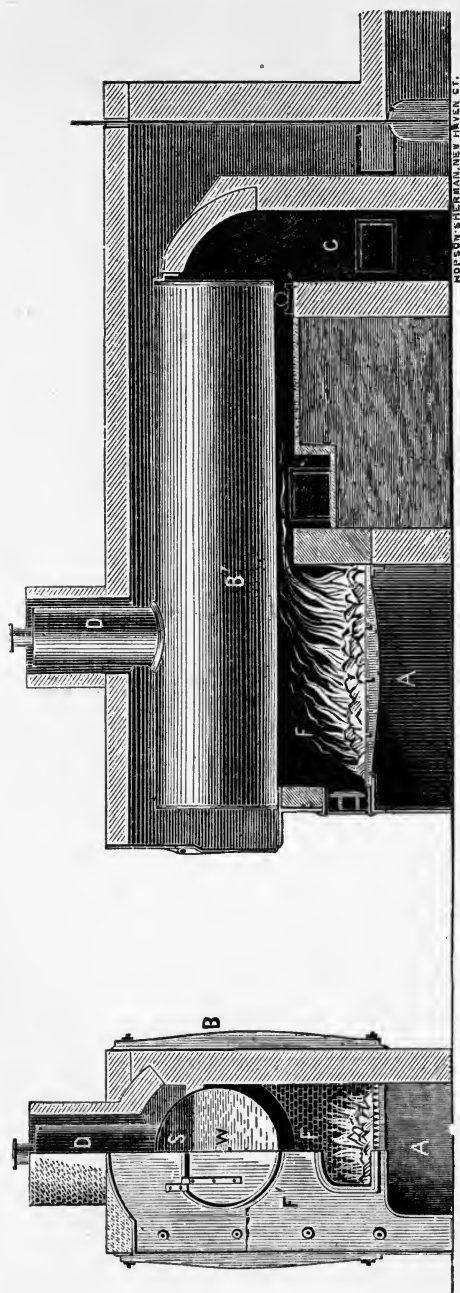


PLATE II.—Plain Cylinder Boiler set in Brick-work.

the complete apparatus to which this term appropriately belongs requires other parts, which, for this class of boilers, is usually supplied by the brick-work setting in which it is mounted.

Plate II., page 123*, represents a cylinder boiler set in brick-work. The front end of the cylinder rests upon a cast-iron frame, called the *Front*, shown in section, and partly in the end elevation of the figure.

The rear end of the cylinder rests upon a brick wall, a roller being placed under this end to permit a slight movement when the cylinder expands or contracts, the object being to prevent the shattering or breaking of the walls by the expansions and contractions when the boiler is alternately heated and cooled.

The setting of a boiler of this character consists usually of a chamber formed by the iron *boiler-front*, two side walls, and a rear closing wall of brick. The side walls are built up parallel to each other, as shown in the longitudinal section and end view, Plate II., at a distance from each other a little greater than the diameter of the shell of the boiler. These walls are held together by clamps (*buck-staves*), connected at the top and bottom by long bolts, as shown at B in the end view.

The space underneath the boiler-shell is divided into two portions by a wall called the *bridge-wall*. The chamber in front of the bridge-wall is devoted to the combustion of the fuel, and is called the *furnace-chamber*. This chamber is divided by the grate into two chambers, the upper being the *furnace* and the lower the *ash-pit*. The upper part of the bridge-wall extends nearly to the shell of the boiler, the top being finished in a cylindrical form, as shown at F in the end view, Plate II. This upper portion is called the *bridge*. It is usually made of fire-bricks, and its office is twofold: to furnish a rear wall to the furnace, and to contract the entrance to the flue to the area proper or suitable for the most efficient draft.

The chamber in rear of the bridge-wall is contracted into a flue by solid filling up nearly to the surface of the cylinder. This flue, formed by the solid bottom, the side walls of the boiler, and the lower half of the cylindrical shell, serves the purpose of conducting the products of combustion to the chimney, and also for the transfer of the heat of these gases to the water in the boiler through the shell. Arches are turned inwardly from the side walls to meet the shell at about the

extremities of the horizontal diameters of the shell, and the flue thus constructed has the shape shown above F in the end view, Plate II.

The furnace F extends from the front back to the bridge-wall. In this class of boilers the width of the furnace is generally equal to the distance between the side walls, and the depth or distance from the front to the bridge is determined by the conveniences of firing, being usually from four to seven feet.

The main flue underneath the boiler terminates in a chamber, C, Plate II., which is connected with the bottom of the chimney. This chamber takes the general name of connection, or smoke-connection. The chimney may be connected with the smoke-connection, or chamber, directly, or it may be isolated and connected through another flue or conduit.

The chimney is a vertical flue, the object of which is usually twofold, viz.: 1st, to cause a draft or supply of air through the furnace, in which its functions are those of a machine operated by the heat of the gases; and 2d, to carry off the products of combustion beyond hurtful or disagreeable proximity.

The principal parts of the plain cylinder boiler, which are also represented wholly, or in part, in nearly all boilers under the same names, are—

1. The *shell*, or external envelope.
2. The *furnace*, F; the chamber in which combustion takes place.
3. The *flue*, or flues; the passages for the heated gases to the chimney.
4. The *bridge*, or rear wall of the furnace, which forms, with the shell of the boiler above it, the boundary of the *draft-area*.
5. The *ash-pit*; the bottom part of the furnace-chamber, which serves as a receptacle for the ashes and cinders, and also as an entrance for air underneath the grate.
6. The *grate*, which is composed of *grate-bars*, or *fire-bars*, forming the bottom of the furnace on which the fuel is laid.
7. The *furnace door*.
8. The *ash-pit door*.
9. The *combustion chamber*. This is an enlargement of the main flue in rear of the bridge, formed by dropping the bottom of this flue a few inches. This part of the main flue is often called the *combustion chamber*, under the assumption that the

combustion of the volatile portions of the fuel is not completed in the furnace, and that an enlargement of this flue into a sort of chamber favors a more thorough mixing of the air and the volatile or combustible gases, and thus produces complete combustion. This is perhaps true where air is admitted by a special arrangement behind the bridge, or through holes in the furnace door. When bituminous coal, or fuel containing a large quantity of volatile matter, is used, some such arrangement for burning the volatile matters should be made.

10. The *smoke-box*, or smoke-connection, is more important in some other classes of boilers than in the plain cylinder boiler, as will appear in the description of those boilers.

11. The *steam-dome* is a vertical chamber set upon the upper surface of the shell, and communicating with it freely through holes in the shell, or through a single large aperture, the object of which is to furnish a chamber for the steam above the steam-space, in which the steam, being removed as far as possible from the liquid water in the boiler, and being in a quiescent state, any particles of water which are carried up with the steam may be separated by precipitation.

In some boilers, especially those for marine purposes, this dome takes the form of an annular space, which is traversed by the smoke-stack or chimney, and is then called the *steam-chimney*.

12. *Water-room* and *steam-room*. The interior of the shell of the boiler is divided by the surface of the water into two spaces, called the *water-room* and *steam-room*, or water-space and steam-space; all the space occupied by water below the water-level being water-space, and the space or spaces above the water-level, including the *steam-dome*, being steam-room.

The water-room of a plain cylinder boiler occupies about $\frac{3}{4}$ of the whole space, and generally in other boilers about $\frac{3}{4}$ of the internal capacity of the shell when the water is at its mean level.

13. *Man-holes*, *hand-holes*. It is important in the management of boilers to examine all accessible parts frequently; and accessibility to every part is a fundamental principle of construction, not only for cleaning, but for facilitating repairs. *Man-holes* are apertures left in the shell, and closed by strong plates which can be removed at will, the opening being large enough to admit a man. *Hand-holes* are smaller openings,

generally near the bottom, which answer the purpose of cleaning by means of tools.

14. *Heating-surface.* In all boilers portions of the iron plates, which form the shell, flues or tubes, are exposed on one side to the heat of the furnace, or the heat of the gases in their course to the chimney, and on the other side to the contact of the water or steam, the transfer of heat being from the furnace and flues to the water through these portions of the iron structure. *A heating-surface in a steam generator may therefore be defined to be any surface which acts as a medium for the transfer of heat from the furnace or gases to the water or steam within the boiler.* The efficiency of such a surface depends, according to the principles which have been enunciated in the chapter on transfer of heat, on *the difference between the temperatures of the furnace or gases and the water, and the thorough and rapid circulation of the fluids and gases in contact with the surfaces.*

Several adjuncts or appurtenances are needed to give efficiency and safety to the boiler, viz.:

15. The *feed apparatus*, which is composed of a pump, an injector, or other device, with the necessary pipes for supplying water to the boiler.

16. The *safety-valve*. A valve opening outwards, and so adjusted and arranged that it will be opened by the internal pressure of the steam, when that pressure exceeds a given amount per square inch.

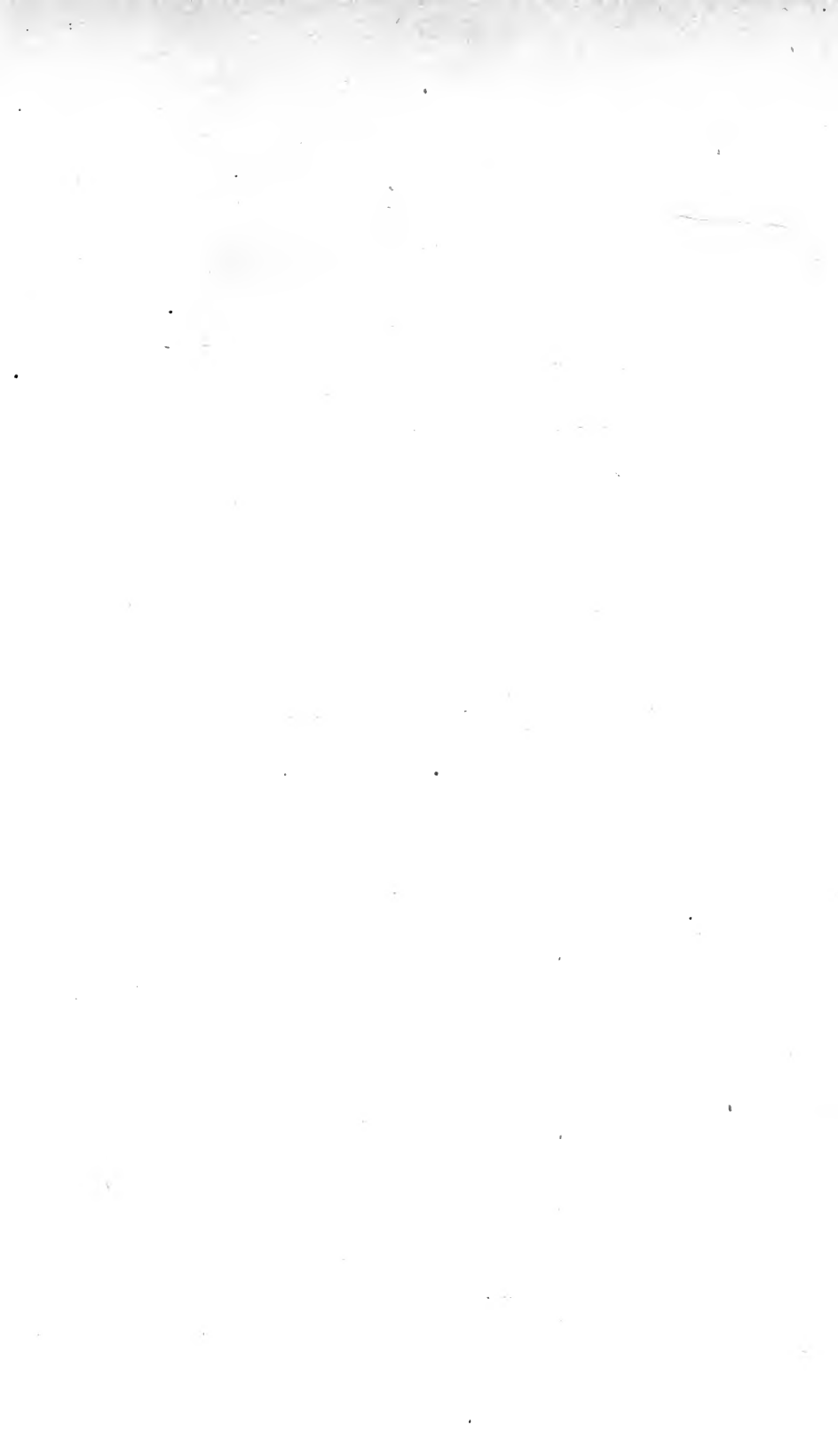
17. The *steam-gauge*. An instrument which exhibits at all times to the eye of the engineer or stoker the pressure of the steam in the boiler.

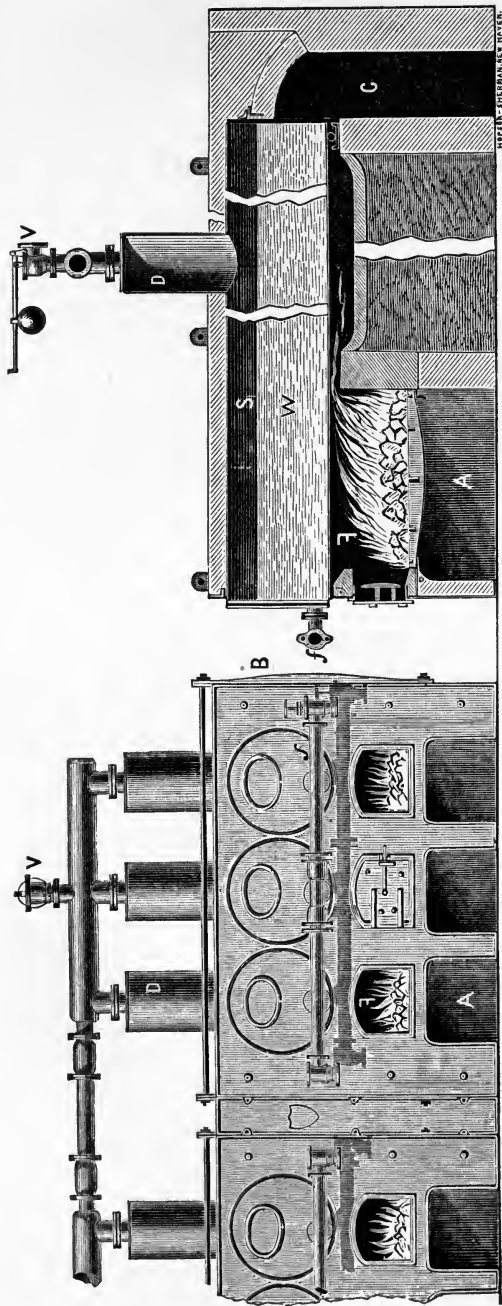
18. *Water-gauges* and *gauge-cocks*, which are intended to show at any instant the level of the water within the boiler.

19. The *low-water detector*. An instrument attached to many boilers, by means of which an alarm is given if the water falls below a given point.

To these "fittings," as they are sometimes called, may be added also the necessary stoker's tools for feeding and managing the furnace, cleaning the flues and tubes, and removing ashes and clinker.

These descriptions of the various parts are applicable to all steam-generators, and, though variously modified, perform the same offices in all. A repetition of the descriptions will therefore





Longitudinal Section.

PLATE III.

End Elevation.

be unnecessary in referring to other kinds of boilers, a reference to the plates being sufficient to show the special combinations in each case.

The *plain cylinder boiler*, which has been described, is the most simple in construction of all boilers, and for this reason it is employed where economy of first cost is desirable, and where economy of fuel is a secondary matter.

The furnaces and flues are external to the shell. The heating-surface comprises all of the lower part of the cylindrical shell which is exposed to the heat of the furnaces and gases; the amount of heating being estimated algebraically by the formula—

$$s = \frac{1}{2} \pi D L$$

s representing the heating-surface, π the number 3.1416, D the diameter, and L the length of the shell. These boilers usually range from 18 inches to 36 inches in diameter, with corresponding lengths of 18 to 36 feet.

For the usual dimensions employed in practice, evaporative powers, and proportions of parts, see page 141.

Plate III., page 127*, represents two sets of three each of such boilers; the end view of four only being shown.

These boilers were made by the Novelty Iron Works, New York, for the Acadia Coal Company of Nova Scotia.

The boilers are each 34 inches diameter and 30 feet long. The grate-bars 5 feet long. The steam-dome 20 by 36 inches. Height from bottom of ash-pit to central line of boilers, 6 feet 2 inches.

Each boiler had 136 feet of heating-surface, and $\frac{6}{10}$ of a cubic foot of steam-space for each square foot of heating-surface.

In such arrangements as those shown in Plate III. the steam-domes are connected by a cross-pipe of large dimensions, in order that there may be free steam communication between the separate boilers.

The construction and mode of setting of the plain cylinder boiler require a greater length for a given amount of heating-surface than any other form of boiler, and on account of the increased expense of brick-work setting, when the length is greatly extended, the increased room necessary, and other at-

tendant disadvantages, economy of fuel is often sacrificed to economy of construction. For other reasons, also, economy of fuel is not to be expected in this form of boiler. Its advantages are cheapness of construction, facility of access for repairs, and general simplicity.

213. **The French Boiler.**—A modification of the plain cylinder boiler, called in England the FRENCH BOILER, and also the ELEPHANT BOILER, and in France the CHAUDIÈRE À BOUILLEURS, is much used on the continent of Europe, and also to some extent in England. It is seldom seen in this country, although a boiler involving the same principal features is often constructed here for shipment to the West India sugar plantations. A sketch of one of these boilers is shown in Plate IV., page 128*. This boiler consists of two cylinders of equal diameter, one above the other, connected by upright cylinders of the same diameter. The mode of setting is best illustrated by Plate V., page 128†, which represents one form of the *French Boiler*.

Fig. 1, Plate V., represents a longitudinal and Fig. 2 a cross-section of this boiler. It consists of one large cylinder, with hemispherical or segmental ends, and one, two, or three smaller cylinders, about half the diameter of the larger, connected with the larger cylinder by two or more vertical cylinders. The lower cylinders receive in France the name "bouilleurs," while the upper or larger is the "chaudière," or boiler. The bouilleurs, the vertical connecting cylinders, and the lower half of the boiler are kept filled with water. The course of the flame and gaseous products of combustion, when there are two bouilleurs, or heaters, is first underneath the bouilleurs from the furnace to the rear end, thence back through a side flue to the front, and returning to the rear by another side flue, forming what is termed a "wheel-draft."

Within the same length the amount of heating-surface is thus much greater than in the simple cylinder boiler. The heating-surface is estimated by taking the total external surface of all the bouilleurs, or heaters, the external surface of the vertical connecting water-tubes, and half the surface of the larger cylinder or boiler.

Besides the advantage of increasing the extent of heating-surface within a given space, this boiler possesses other special advantages which have rendered it deservedly popular where it has been most used. One of these important advantages

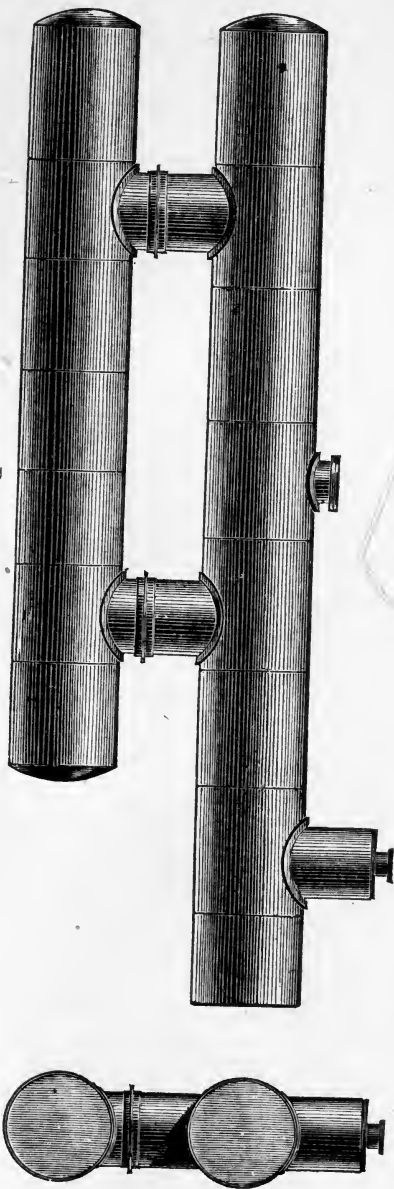


PLATE IV.—See page 128.

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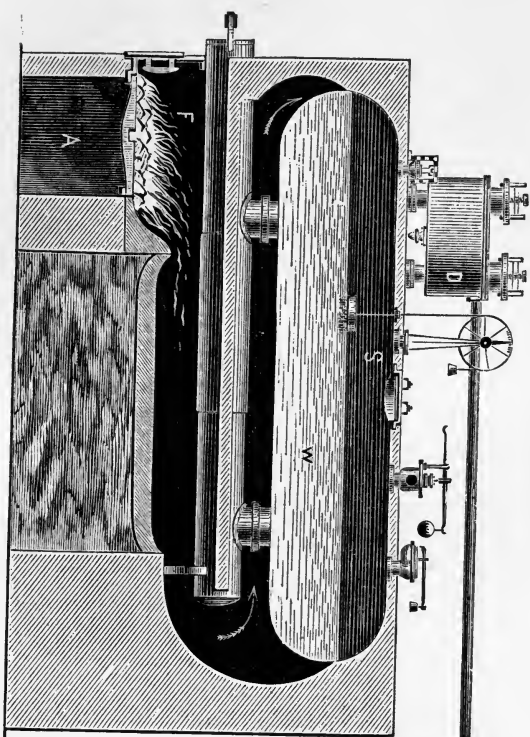


Fig. 1.

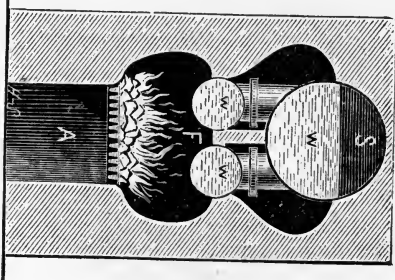
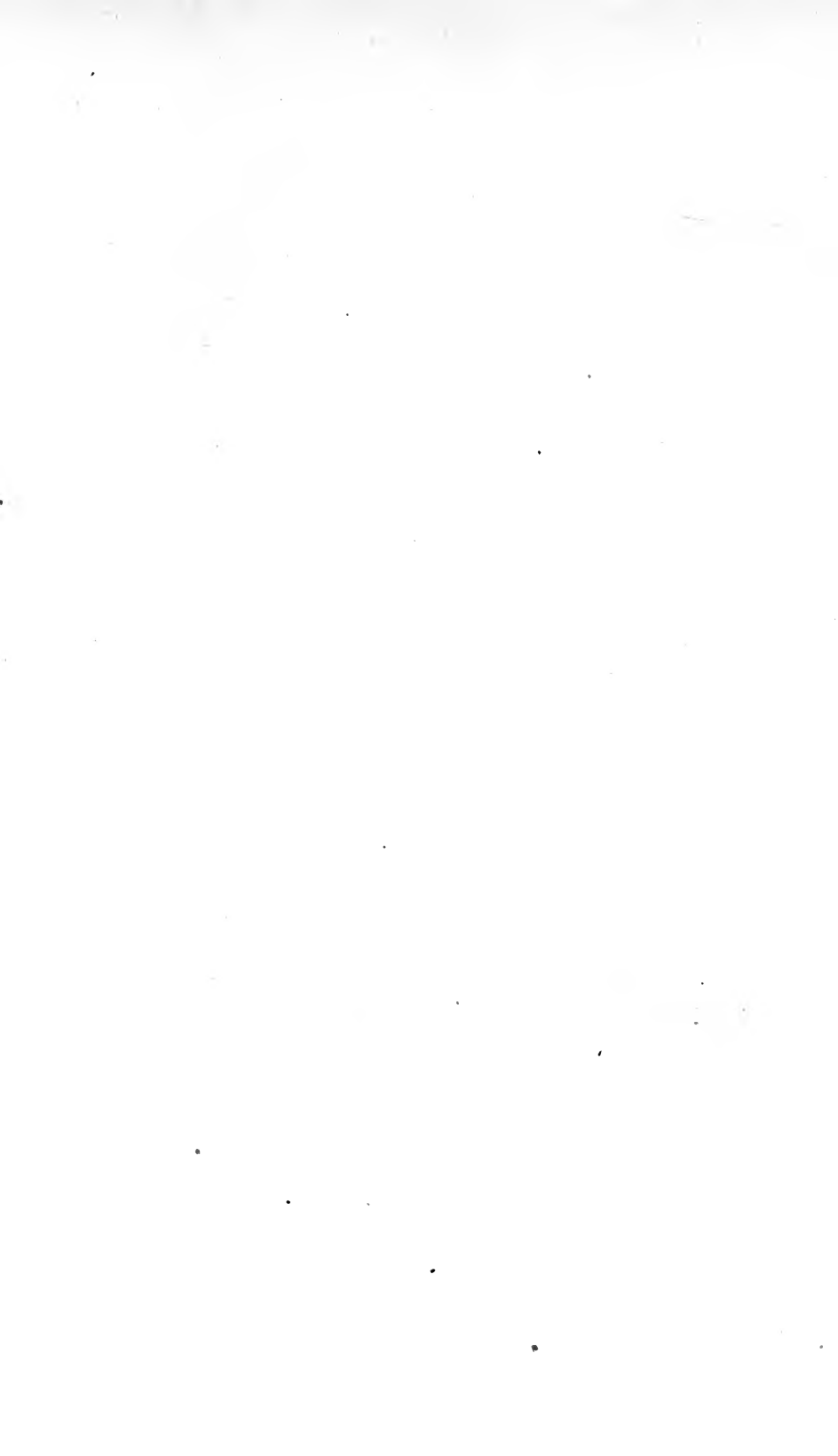


Fig. 2.

PLATE V.—French Boiler (Chaudière à Bouilleurs).





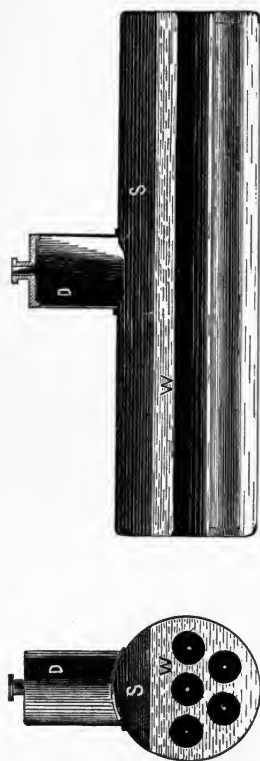


PLATE VI.—Shell of Cylinder-Flue Boiler with Five Flues.
Fig. 1.

Fig. 2.

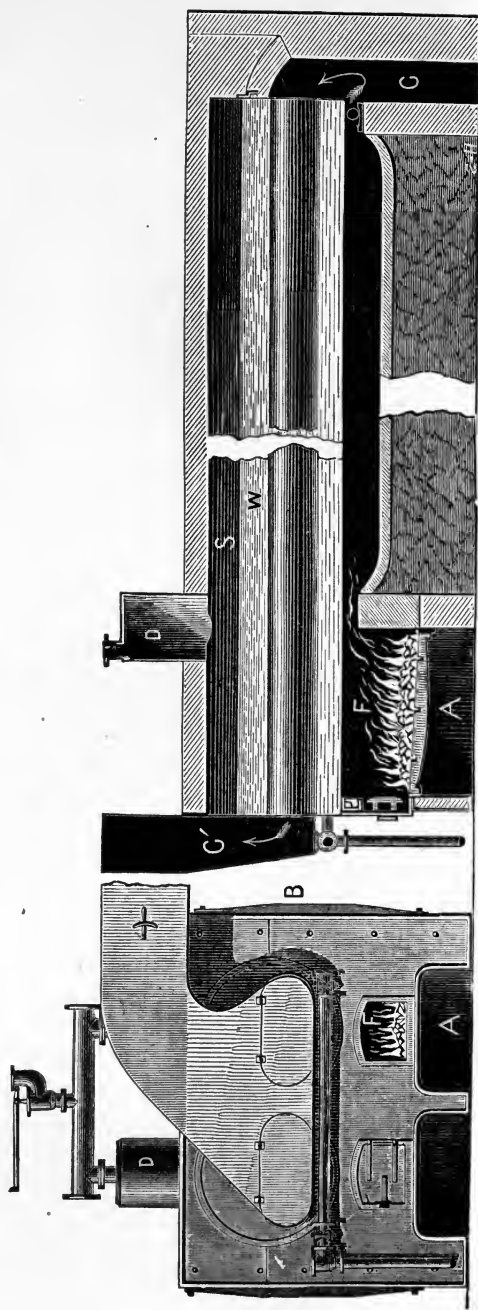


PLATE VI. a.—Cylinder-Flue Boiler. Two Boilers set in Brick-work.

is, that the smaller cylinders only are exposed to the initial temperatures of the furnace and gases, while the larger are exposed to a less heat. The smaller cylinders can thus be easily repaired and cleaned, or even replaced, and as the larger cylinders are less exposed to injury, they last longer than the smaller cylinders.

According to Morin and Tresca, *two* bouilleurs form the most convenient and efficient arrangement, though one, and three are often employed.

214. *Cylinder-Flue Boiler*.—This modification of the cylinder boiler is characterized by an arrangement of one or more internal flues of large diameter, running longitudinally within the shell in such a manner that the heated gases pass once through these flues, and once through one or more flues external to the shell.

Plate VI., page 129*, represents the shell and internal flues of one of these boilers as it comes from the manufacturer's hands, and Plate VI. *a*, a set of two cylinder-flue boilers set in brick-work.

The boilers represented by Plate VI. *a*, were made for a high-pressure engine, by the Novelty Iron Works, in 1866. The length of the shell of each is 26 feet; the diameter, 4 feet; diameter of internal flues, 16 inches; length of grate-bars, 4 feet 10 inches; height of crown of furnace above grate at front end of grate-bars, 2 feet; dome, 24 × 30 inches; heating-surface, one-half the surface of the shell added to the total surface of the flues, or,

$$s = \pi R L + 4 \pi r L;$$

R representing the radius of the shell, r the radius of the flues, and L the length of the boiler.

For the above-named dimensions the total heating-surface for each boiler will be approximately 380 square feet. There is approximately 80 cubic feet of steam-room in each boiler, and 17 square feet of heating-surface to 1 square foot of grate-surface. The ash-pit *A*, the furnace *F*, the smoke-connection *C*, the water-space *W*, the steam-space *S*, and the steam-dome *D*, are indicated, as in all the other plates, by these letters respectively; the flues or conduits for the flame and gases to the chimney being represented by the black shading, and the direction by the arrows. The brick-work setting is the same

as for the plain cylinder boiler. In this class of boilers the heated gases pass underneath the shell to the first smoke-box or connection, and return through the internal flues to the point where there is a second smoke-box C', from which the gases are led by a side flue, made of light iron, to the chimney. Where the heated gases pass from one flue into two or more, or from one set of flues or tubes, by a return, to another set, the smoke-connection serves to equalize the draft in all the flues or tubes, and should be arranged with this view.

Plate VII., page 130*, gives a longitudinal section and an end elevation of a single cylinder-flue boiler, mounted in brick-work, made in 1863: length, 24 feet 8 inches; diameter, 42 inches; steam-dome, 24 inches diameter; grate-bars, 4 feet 10 inches long; width of furnace, 4 feet. This boiler is provided with two flues, each 13 inches in diameter. This and the following plate are introduced to show the different modes of constructing the cast-iron boiler-fronts.

Plate VIII., page 130†, represents another construction of boiler-front for the same class of boiler. In this example there are two boilers, side by side, as in Plate VI. For dimensions in current use, proportion of parts, and evaporative powers, see page 141.

215. **The Cornish Boiler.**—This is a variety of the cylinder-flue boiler which has been long in use in England for stationary engines. It differs from the American boiler of the same class in having an *internal furnace*. The furnace, or furnaces, are placed within the front end of a large flue, which extends through the boiler from the front to the rear end.

Plate IX., page 130‡, represents a longitudinal section and sectional elevation of the Cornish boiler. The bridge is built of fire-bricks within the large flue, and the heated gases pass directly through the flue, which is entirely surrounded by water, to the rear end. Returning by a split-draft along the sides of the boiler, the gases pass a third time along the whole length of the boiler, from front to rear, underneath the shell. This is the usual arrangement of the draft, but it is often varied. The diameter of the flue is usually about $\frac{6}{10}$ the diameter of the shell of the boiler. The crown of the furnace, and a portion of the flue beyond the bridge, are sometimes lined with brick to prevent too rapid cooling of the flame before the combustion of the gases is complete. These boilers are some-

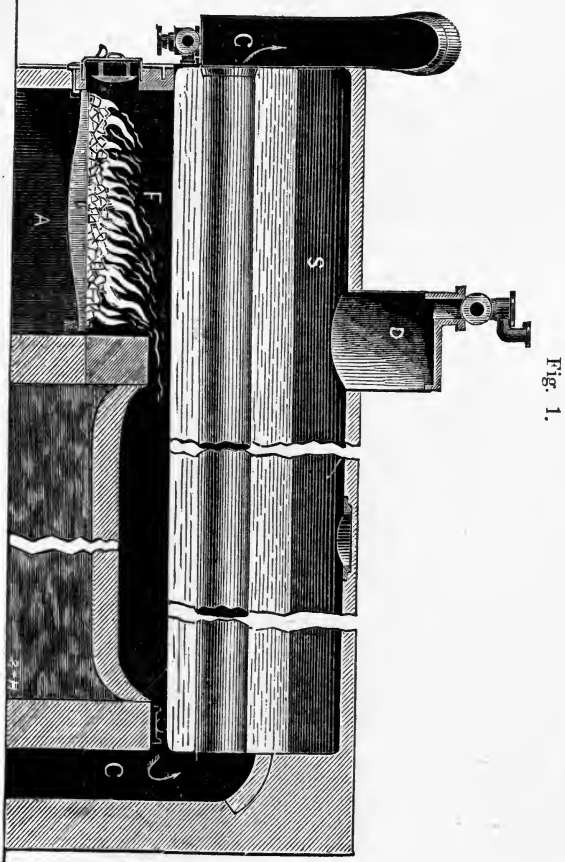
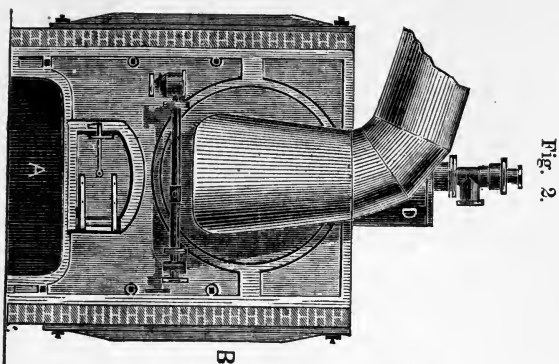


PLATE VII.—Cylinder-Flue Boiler.

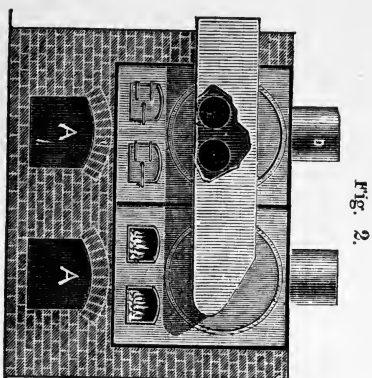


Fig. 2.

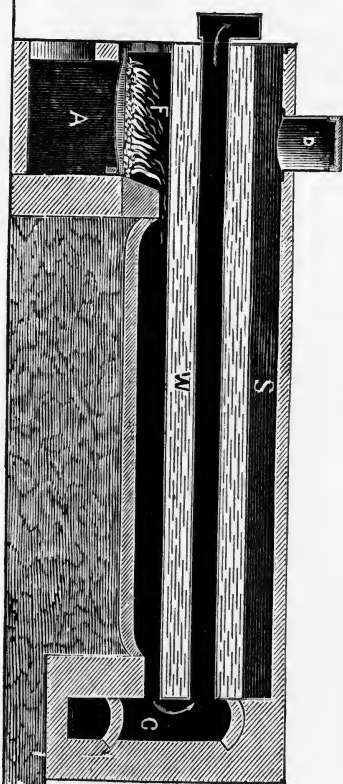


Fig. 1.

PLATE VIII.—Cylinder-Fine Boiler.

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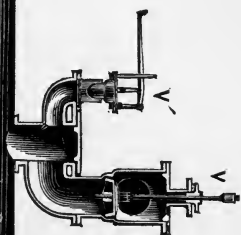


Fig. 1.



Fig. 2.

PLATE IX.—The Cornish Boiler.

times made with two cylindrical flues, and sometimes with two internal furnaces leading into a single flue.

The efficiency of these boilers is about the same as that of the ordinary American form first described. With very low rates of combustion the economic efficiency is increased to 9 to 10 pounds of water evaporated for each pound of coal burned—the ordinary evaporation of cylinder-flue boilers being about 8 pounds of water evaporated for each pound of coal,—the rate of combustion being about 10 to 12 pounds of coal on each square foot of grate-surface per hour. The furnaces of the *Double Furnace* Cornish boiler are usually fired alternately, in order to procure a more complete combustion of the volatile gases in each furnace.

The principal objection to the Cornish boiler is the large diameter of the flue or flues, which renders them liable to collapse, especially at the high pressures employed at the present day.

216. Cylinder-Tubular Boiler.—Boilers of this class differ so little from the common cylinder-flue boiler described above, that they might with propriety be classed with them. They form, however, the basis of a variety of modified forms, and in practice there is a difference between flues and tubes, not only in mechanical construction, but also in the modes of connecting the flues and tubes with the end-plates of the boilers, of which they form parts. Flues differ from tubes in being generally of larger dimensions. They are usually constructed of metallic plates rolled into the cylindrical form, and then riveted together as in the construction of the shell of the plain cylinder boiler. Tubes, on the other hand, are usually constructed by lapping and *welding* the edges, instead of riveting them; special machines being used for this purpose. Tubes thus constructed are now made from the smallest form of *pipes* to a diameter of 6 and 8 inches.

Flues and large tubes are usually attached to the heads or end-plates by stovepipe-riveted joints or by angle-iron rings, while tubes of the smaller diameters are usually inserted at the ends into neatly drilled holes in the *tube sheets* or end-plates, and the end of the tube is then *expanded*, by a special tool called the *tube expander*, to the extreme extent practicable, so that the external surface of the tube at the joint not only closely fits the hole, but the material of the tube is expanded

into annular welts on each side of the plate. The external edge of the tube is then turned over, or calked, by another tool.

Flues may always be regarded as conduits for heated gases or smoke, while *tubes* may conduct gases or may remain filled with water and act as passages for liquid circulation, while heated gases come in contact with their external surfaces; in both cases acting as *heating-surfaces*. In estimating heating-surfaces the *fire-surface*, not the water-surface, is taken.

Thus, in regard to size or diameter, mechanical construction, mode of attachment, and in functions, the tube may differ from the flue.

The common cylinder-tubular boiler is in every respect similar to the cylinder-flue boiler, except that, instead of large internal return flues, there are many returning tubes, and the gases, after having passed through the main external flue underneath the boiler, return through these tubes to the front, where the tubes all terminate in a common smoke-connection or chamber. All the parts, and the mode of setting, are the same as for the cylinder-flue boiler. The employment of tubes instead of large flues permits of a still further diminution of the external length of shell for the same amount of heating-surface, and permits of the use of higher pressures of steam with greater safety.

This form of boiler, with its various modifications, is probably in more universal use at the present day than any other form of cylinder boiler. It constitutes the basis of all *marine-tubular* boilers, even where the shell is not cylindrical, and for stationary engines is very extensively used.

Plate X., page 132*, gives a longitudinal and cross-section of the shell of a cylinder-tubular boiler. This plate represents a boiler of the following dimensions: Length, 14 feet; diameter, 47 inches; dome, 24 x 36 inches; it has 40 tubes $3\frac{1}{2}$ inches outside diameter.

Plate XI., page 132*, represents another shell of this character: 16 feet in length; 51 inches outside diameter, with 32 4-inch tubes. This boiler was built for a manufacturing establishment where wood-shavings constituted the fuel.

Plates XII., XIII., XIV., and XV., pages 132†, 132‡, 132§, 132||, represent cylinder-tubular boilers set in brick-work. The sections and end elevations show the construction of the walls,

Fig. 2.

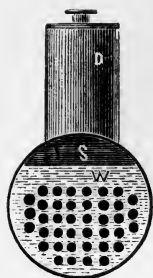


Fig. 1.

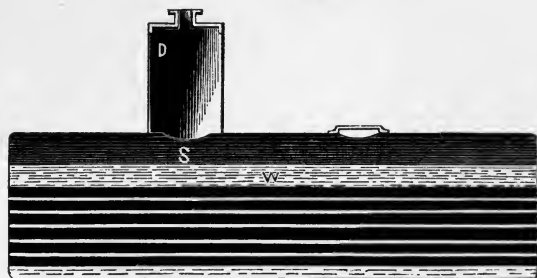


PLATE X.—Shell of Cylinder-Tubular Boiler.

Fig. 2.

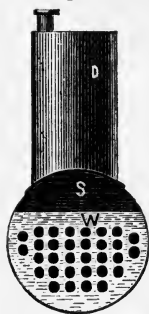


Fig. 1.

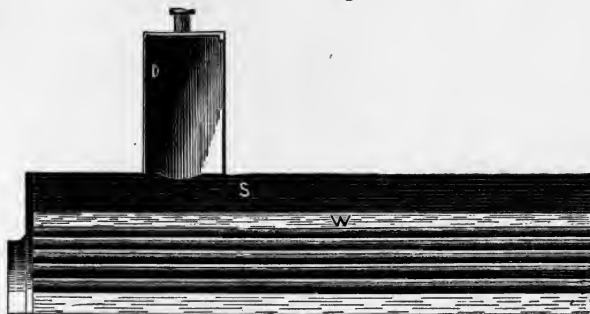


PLATE XI.—Shell of Cylinder-Tubular Boiler.



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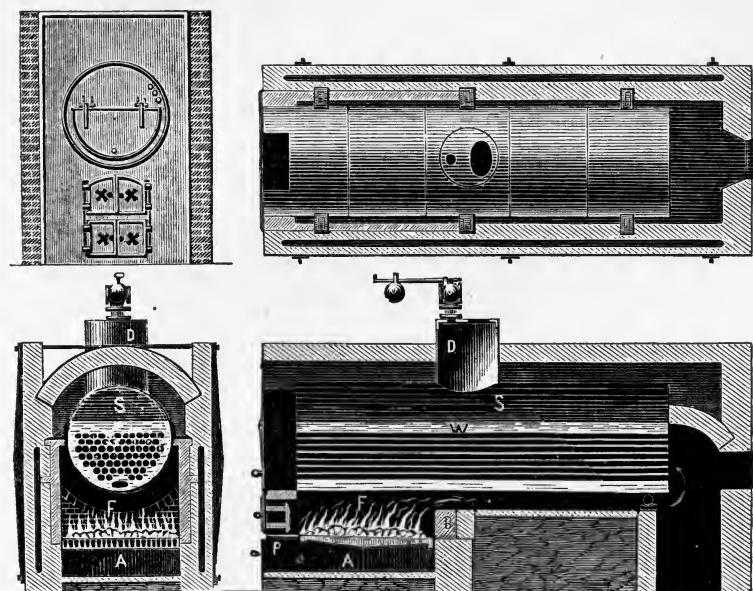


PLATE XII.—Cylinder-Tubular Boiler set in Brick-work.

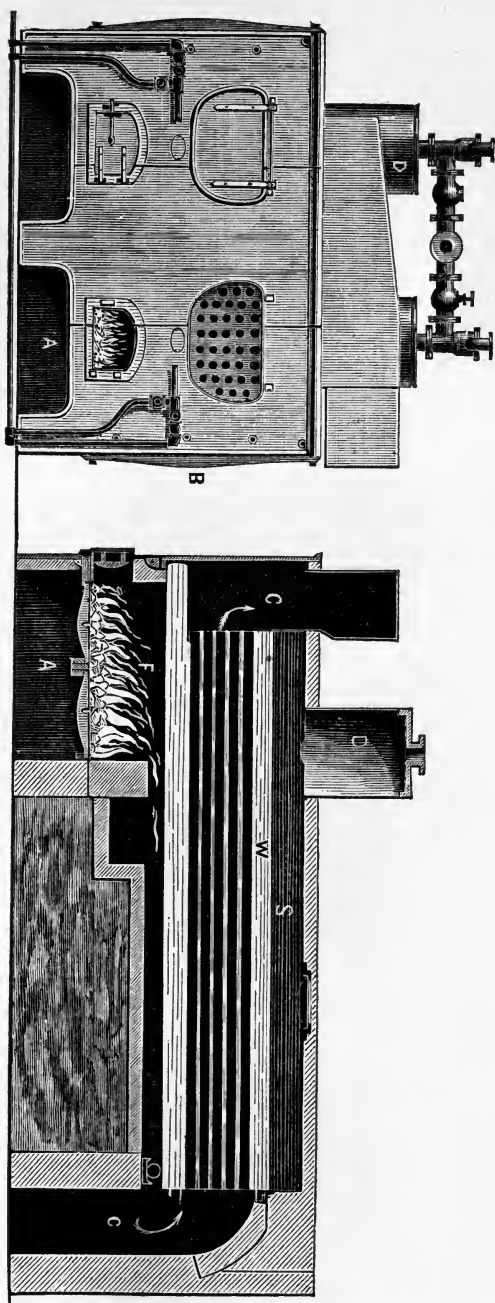


PLATE XIII.—Two Cylinder-Tubular Boilers set in Brick-work.



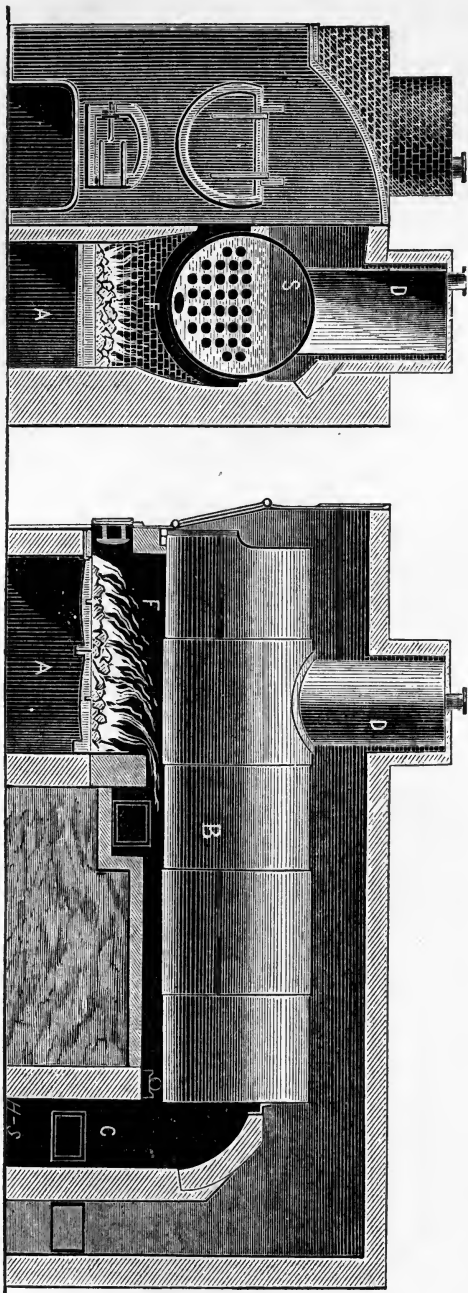
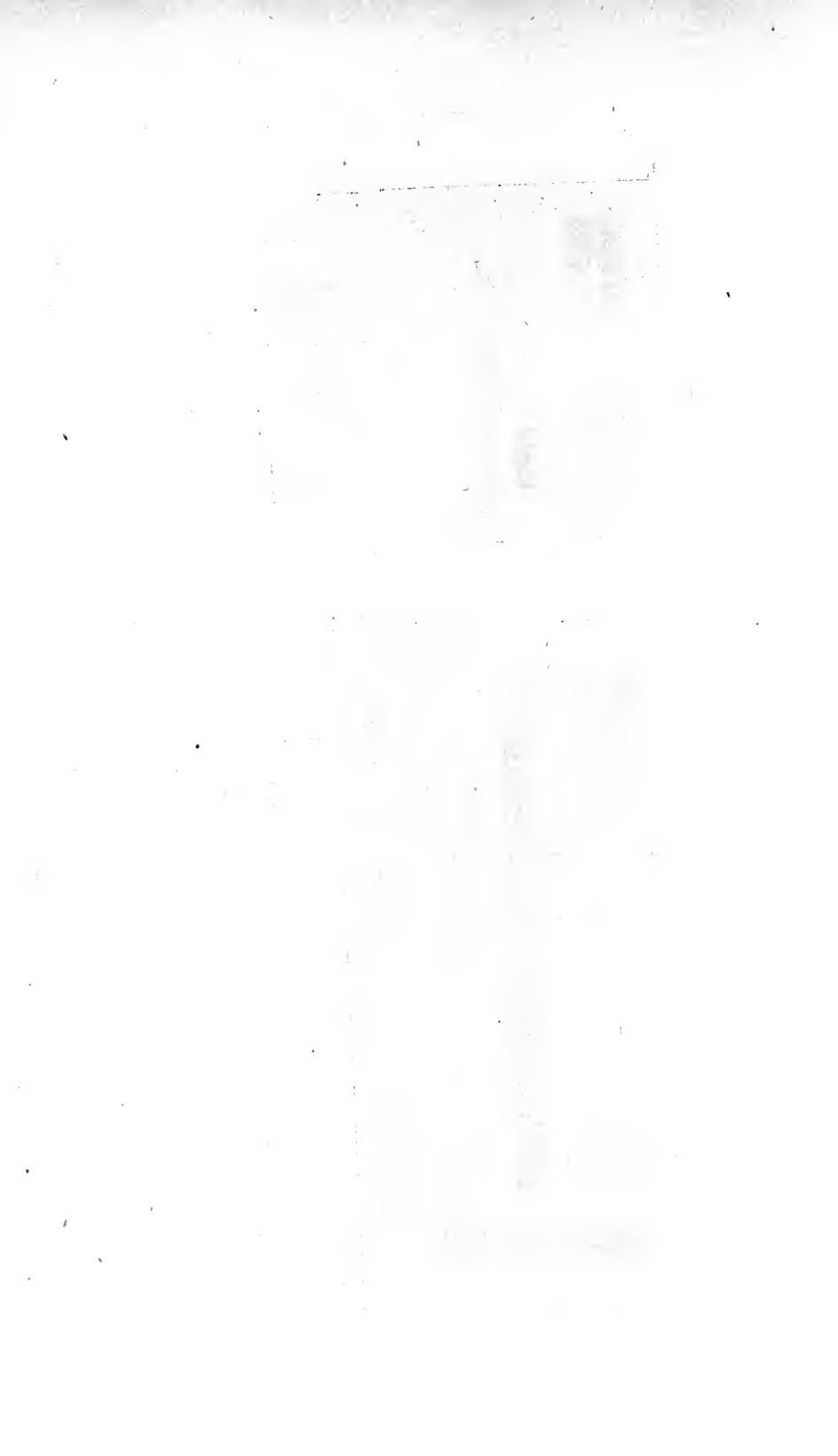


PLATE XIV.—Two Cylinder-Tubular Boilers set in Brick-work.



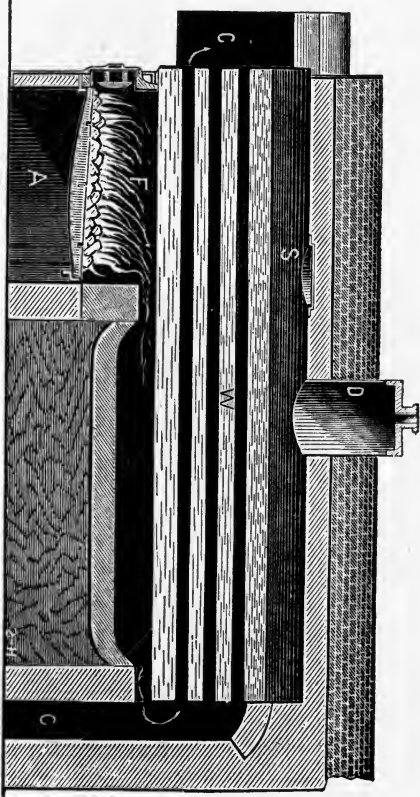
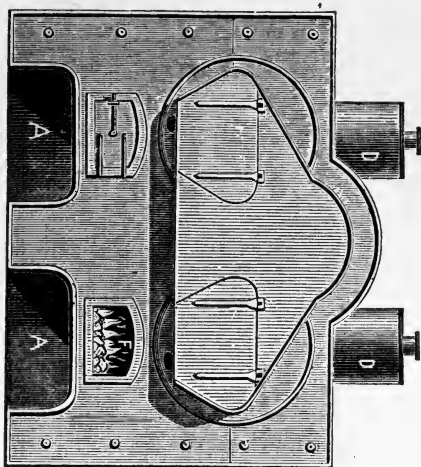
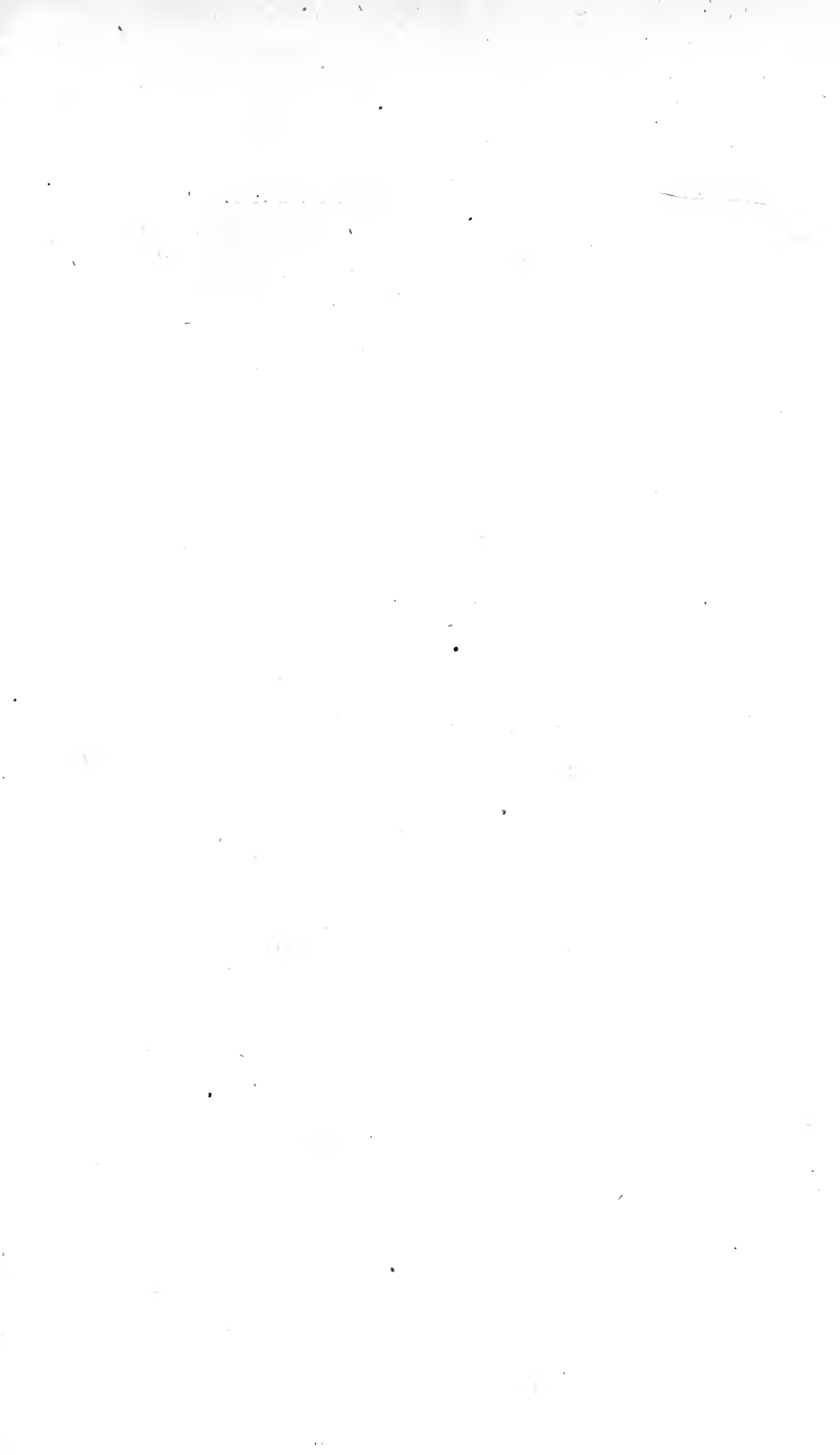


PLATE XV.—Two Cylinder-Tubular Boilers set in Brick-work.



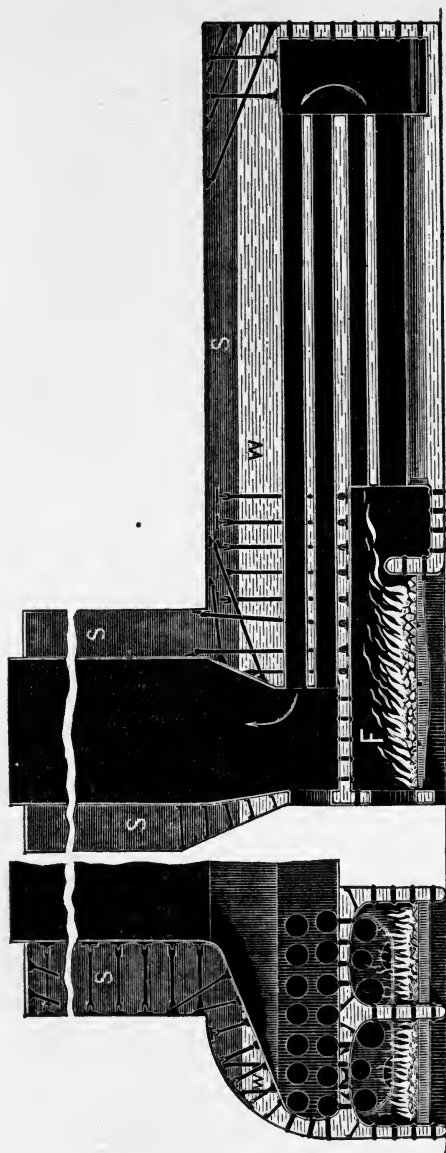
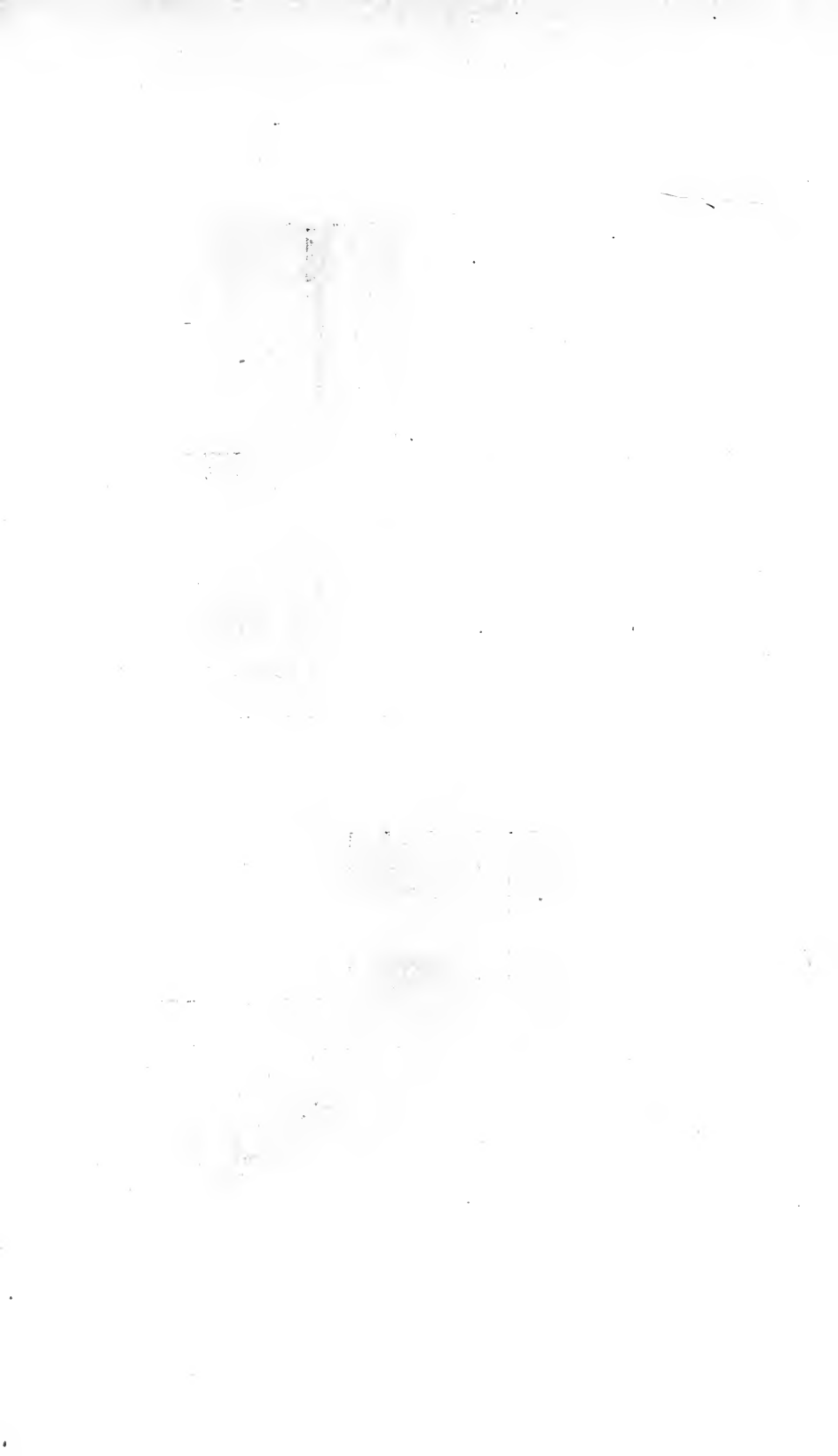


PLATE XVI. — Return-Flue Boiler.



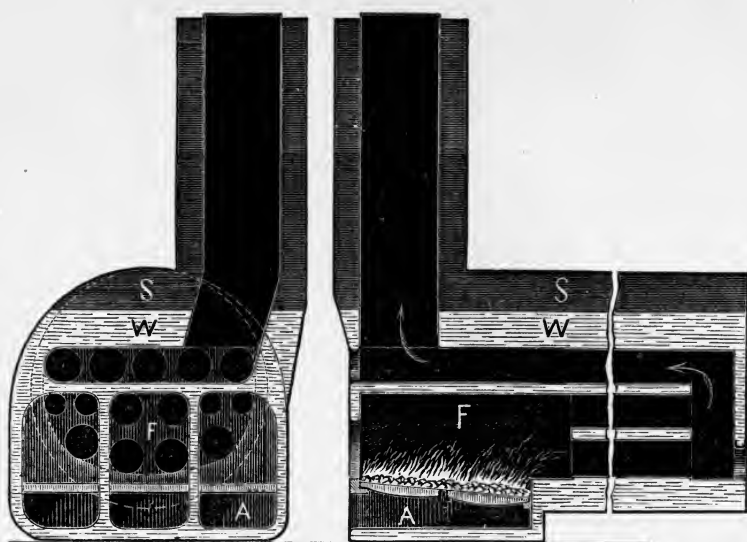


PLATE XVII.—Return-Flue Boiler.

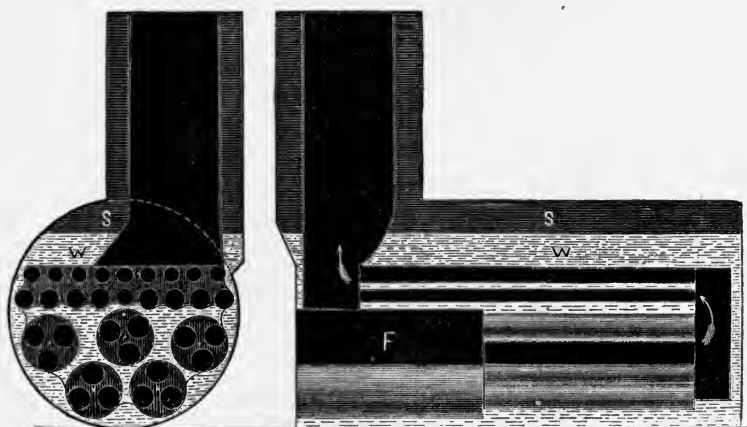


PLATE XVIII.—Return-Flue Boiler.

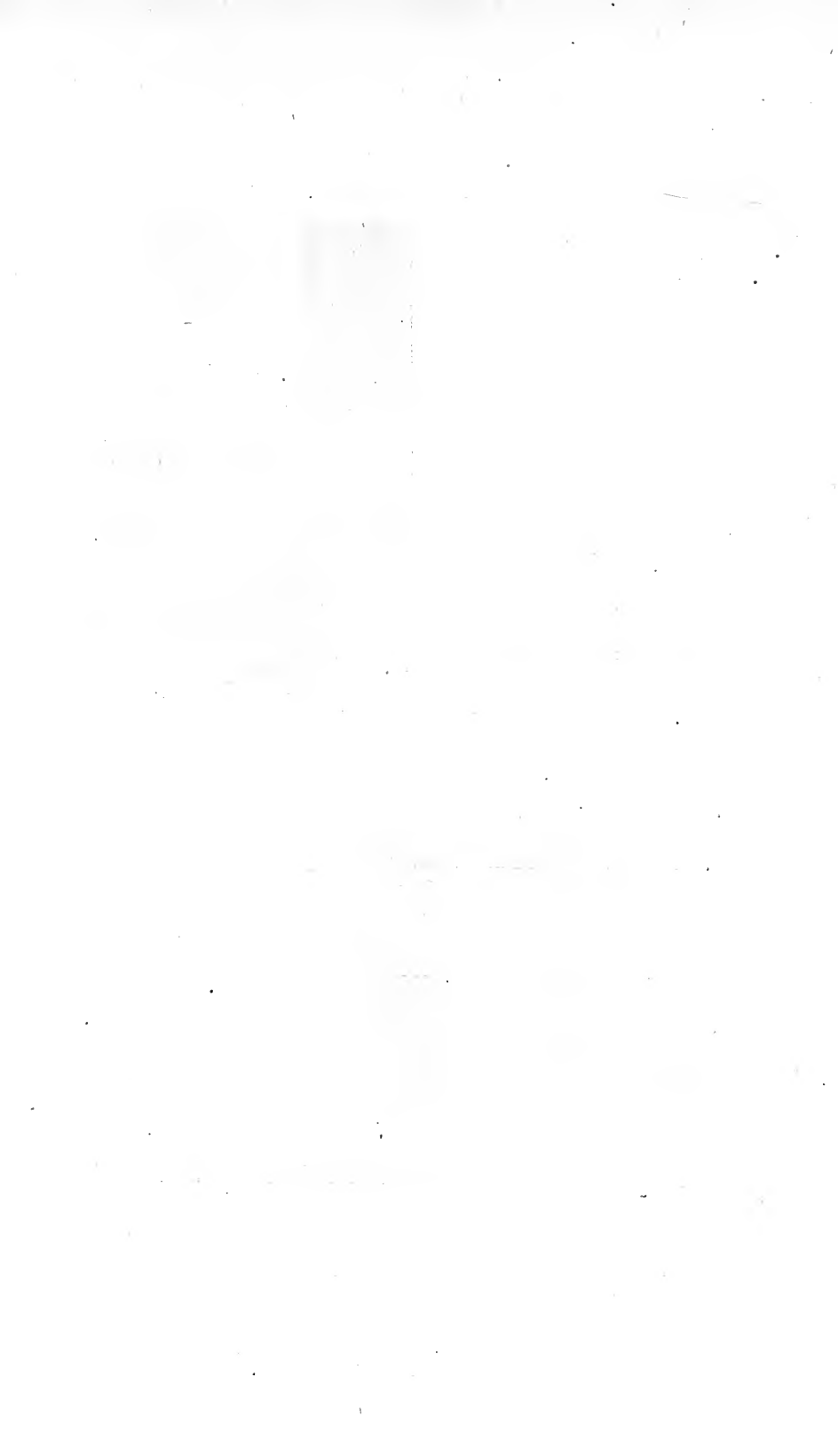
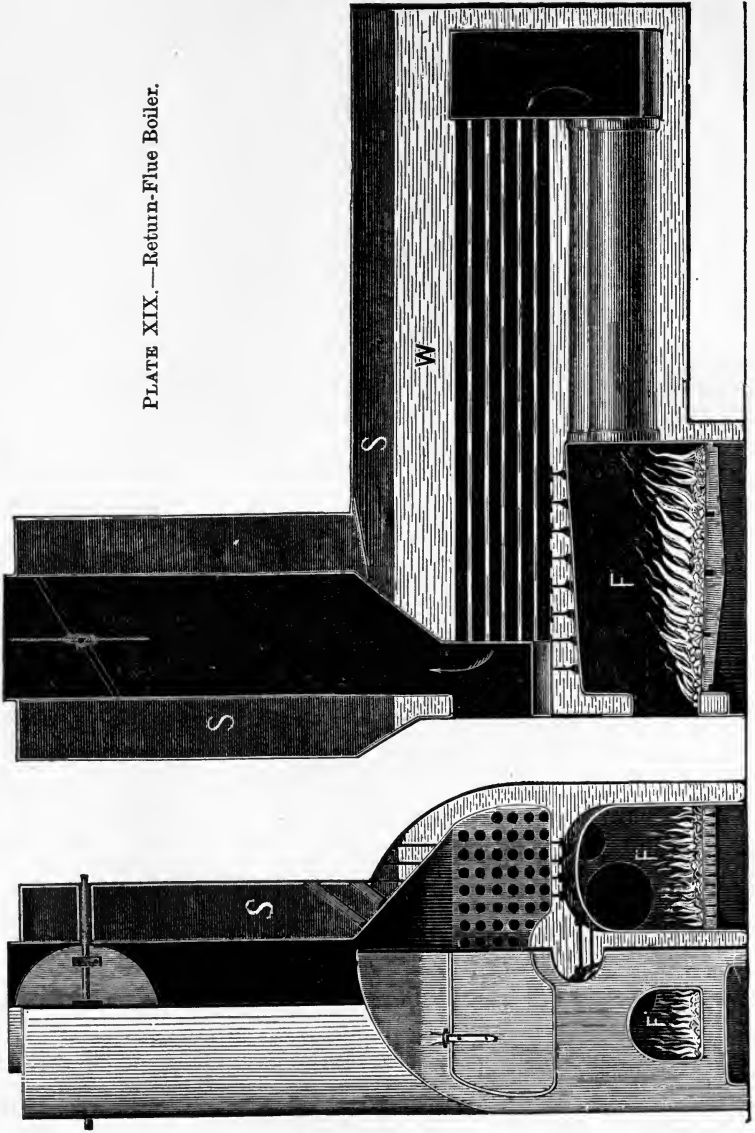


PLATE XIX.—Return-Fine Boiler.



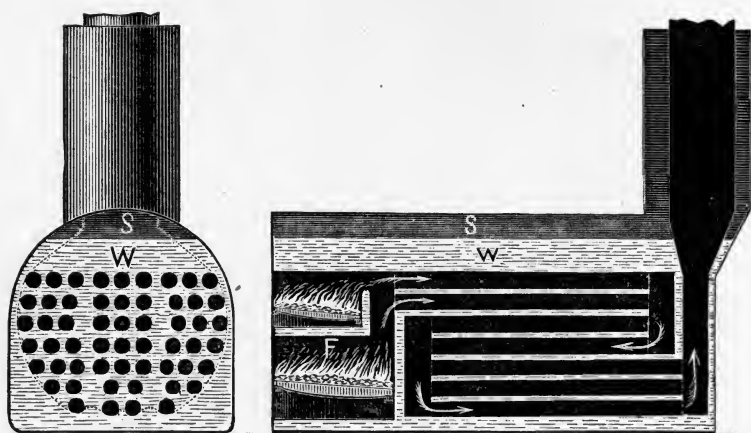


PLATE XX.—Drop Return-Flue Boiler.

the furnace and flues, the arch of brick covering the boiler, and other features of construction.

Plate XII. page 132†, represents a boiler in which the furnace-gases, after returning through the tubes to the front of the boiler, pass back between the brick arch and the top of the boiler to the chimney.

Plate XIII., page 132‡, represents a set of two cylinder-tubular boilers mounted together. The shells of these boilers are 16 feet in length, with an extension of the water-space in front over the furnace of two feet, to form the smoke-box; diameter of shell, 4 feet; number of 3-inch tubes, 36; dome, 30 × 36 inches; grate-bars in double length; furnaces, each 4 feet 4 inches wide and 5 feet deep; height of crown of furnace above grate, 26 inches. The bridge-walls of all furnaces set in brick-work are usually 12 inches thick, and are topped out above the grate with fire-bricks. The domes of these boilers are connected by a pipe of large diameter, in which is placed a stop-valve. The feed-pipes are shown in front as in other examples.

Plate XIV., page 132§, shows a pair of such boilers set in brick-work, the domes being surrounded by brick-work. This plate exhibits the external appearance of the shell as it is mounted.

Plate XV., page 132||, represents a pair of boilers, each 16 feet long and 48 inches diameter, and having 33 tubes, each 4 inches diameter. The furnaces in this boiler are each 5 feet in depth, and 4½ wide; the domes 24 inches diameter.

In the cylinder-tubular boilers the heating-surface is found by adding to half the external surface of the shell, the aggregate internal surfaces of the tubes, and is represented by the following formula:

$$s = \pi R L + n 2 \pi r L$$

in which s represents the heating-surface; R , the radius of the shell; r , the internal radius of the tubes; L , the length of the boiler, and n , the number of tubes.

For dimensions, proportions, and evaporative powers of these boilers, see page 141.

217. Plates XVI., XVII., XVIII., XIX., and XX. represent varieties of a class of boilers which are known as *Return-Flue Boilers*. They were at one time in very general use in steam-boats and steamships in this country, and are still employed to

a considerable extent. They are characterized by having internal furnaces and internal flues, no external furnaces or brick-work being attached to the boilers. Constructed in this manner, they are ready for use as they come from the hands of the manufacturer.

The shell in these boilers is made sufficiently large to receive within it the direct flues from the furnace, from front to rear, and also the return flues; the arrangements being as exhibited in the several plates. Two or more furnaces may be arranged side by side, as in Plates XVI., XVII., and XIX., or the furnaces may be arranged in upper and lower levels, as in Plates XVIII. and XX.

218. Plate XX. represents a boiler which receives the name of *Drop Return*, from the downward course of the flues in passing from the furnaces to the chimney.

Boilers of this class, when applied to marine purposes, instead of a steam-dome, have what is called a *steam-chimney*. This is always at one end, in order that the smoke-chimney may pass up through the steam-chimney. The effect of this is to dry and slightly superheat the steam before it is drawn off to the engine.

These boilers having large diameters, it is necessary to strengthen the various parts by stays, as shown in Plate XVI. Around the furnaces the plates are stayed and kept in position by *sockets* and bolts, the sockets acting as struts and the bolts as stays.

219. Plate XIX. represents a boiler in which there are direct flues and return tubes. In these boilers the smoke-connections are important. They not only serve to equalize the draft through the flues and tubes, but the bounding-surfaces perform to some extent the functions of heating-surfaces, and are generally estimated as part of the heating-surfaces.

The total heating-surface in these boilers is found by adding together the interior surface of the furnace, the interior surfaces of the direct and return flues, and the surfaces of the smoke-connections. No general formula is applicable, but the computation is readily made in any special construction. There is often a combustion-chamber in boilers of this class, behind the furnace, which is separated from the furnace by a water-bridge. *Water-bottoms* and *water-legs* were formerly constructed, the former as security against fire; but experience has shown that,

owing to a want of circulation, and the exposure of these parts to external moisture, they soon became corroded and required frequent repairs, and it is now considered best to confine water only to the spaces within which there is a circulation, and to provide security against fire by covering the floor on which the boiler rests with a suitable non-conducting and non-combustible material. The following are the dimensions of the boilers represented in Plates XVI., XVII., XVIII., and XX.:

Boiler represented in Plate XVI: Length, 25 feet over all; diameter of shell, 7 feet 6 inches; diameter of direct flues (five to each furnace), 12, 12, 12, $9\frac{1}{2}$, $8\frac{1}{2}$ inches; diameter of return flues, $8\frac{3}{4}$ inches; number of return flues, 14; depth of grates, 7 feet; width of grates, $40\frac{3}{4}$ inches; diameter of chimney, $56\frac{1}{2}$ inches; steam-chimney, 7 feet 9 inches diameter, 12 feet high; length of direct flues, 11 feet 11 inches; length of return flues, 18 feet 5 inches; first combustion chamber behind the bridge, 28 inches deep; first smoke-connection, 30 inches deep; second smoke-connection, or uptake, 40 inches deep. This boiler was built for the steamer Jesse Hoyt, a side-wheel river steamer, in May, 1867.

Plate XVII., a boiler built for the ocean steamer Southerner. Length over all, 26 feet; length of direct flues, 15 feet 6 inches; diameter of direct flues, 6 of 16 inches, 4 of 11 inches; return flues, 20 feet 3 inches in length, 16 inches diameter; shell of boiler, 9 feet diameter; depth of furnace, 7 feet 4 inches; diameter of chimney, 3 feet; diameter of steam-chimney, 5 feet; height of steam-chimney, 9 feet 6 inches; height of boiler to top of shell, 10 feet 3 inches. This boiler belonged to a set of two, each of which had 58.76 square feet grate-surface; 10.44 square feet fire-surface; area of cross-section (draft area) of direct flues, 7 square feet; return flues, 11.6 square feet; uptake, 7 feet; weight of each boiler, 39,000 pounds; heating surface of each boiler, 1044.6 square feet.

Plate XVIII. represents one of two boilers built for the ocean steamship Nashville. Whole length, 24 feet; diameter of shell, 12 feet 3 inches; length of direct flues, 11 feet 8 inches; return flues, 18 feet 4 inches; number of furnaces, 5; number of direct flues from each furnace, 3; diameter of direct flues, 15 inches; diameter of return flues, 13 and 11 inches; number of return flues, 13 inches diam., 9; number 11 inches diam., 9; diameter of chimney, 4 feet 10 inches;

diameter of steam-chimney, 7 feet 4 inches; height of steam-chimney above shell, 10 feet; grate-surface, each boiler, 150 square feet; heating or fire surface, each boiler, 2,166 square feet; draft area, direct flues, 18.4 square feet; return flues, 13.7; uptake, 18.3 square feet.

Plate XX. represents one of the boilers of the steamship *Arago*, formerly running between New York and Liverpool; built 1855. Whole length, 29.3 feet; flues, 16 feet 7 inches long, and 13 inches diameter; number of furnaces, 3; number of direct flues, 18; number on first-drop return, 18; number on second-drop return, 19; aggregate draft area, first and second sets, $16\frac{1}{2}$ square feet, and of the second, 17.7 square feet; diameter of chimney, 4 feet 9 inches; diameter of steam-chimney, 7 feet 3 inches; smoke-connections, 21 inches deep; fire-surface of each boiler, 4,320 square feet; grate-surface, 162 square feet.

220. **Marine Tubular Boiler.**—Plate XXI., page 136*, represents a modification of the return-tubular boiler suited to marine purposes. The limitation of space in the hold of a ship renders it necessary to contract the boiler-space as much as possible, and the form of boiler adopted, generally, is that illustrated in Plate XXI. The external shell receives the general form of which Fig. 1 is a cross-section and Fig. 2 an elevation. The arrangement of the furnaces, flues, tubes, and smoke-connections, are as shown in the figures. In boilers of this character, each boiler contains several furnaces, and two or more boilers are usually set together on opposite sides of the hold of the vessel, in such a manner as to have a common chimney.

In the example given there are eight furnaces in the boiler. The second smoke-connection runs the entire length of the boiler along the front and leads to the chimney, which is placed near one end. The boiler represented is one of a set of four made for the side-wheel steamship *Baltic*. The peculiar form of the shell is adapted to the space allotted to the boiler along the side of the ship's hold, as is usual in such cases. This form not being cylindrical, it is necessary to brace all flat surfaces which receive pressure. The manner in which this is accomplished is exhibited in Fig. 4, page 137*, which represents the bracing of the boiler illustrated in Plate XXI. The roof-plates of these boilers are sometimes supported by iron pillars or struts extending from the roof to the bottom, between the furnaces.

Fig. 2.

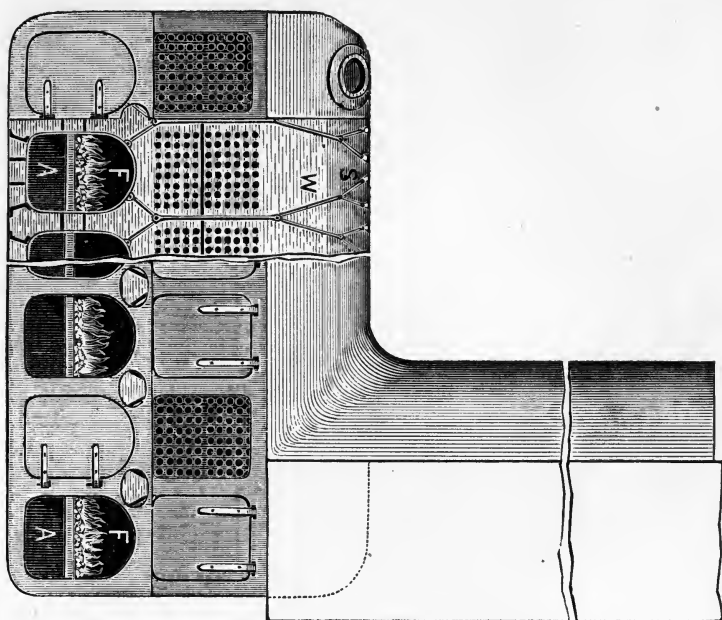
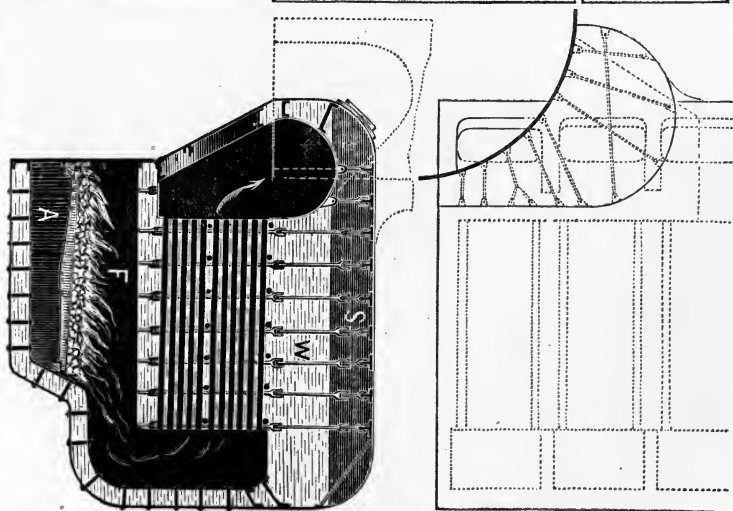
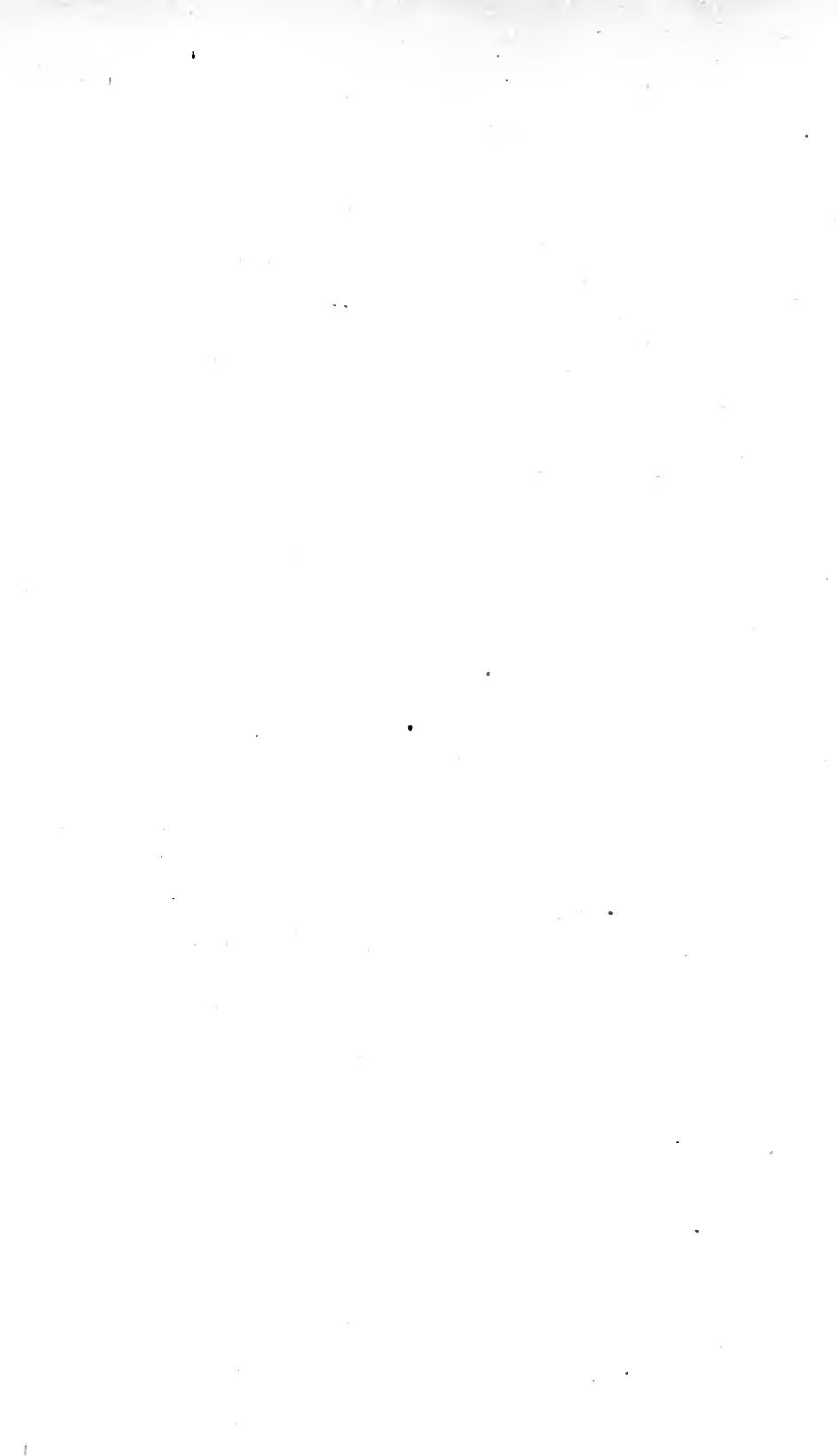


Fig. 1.





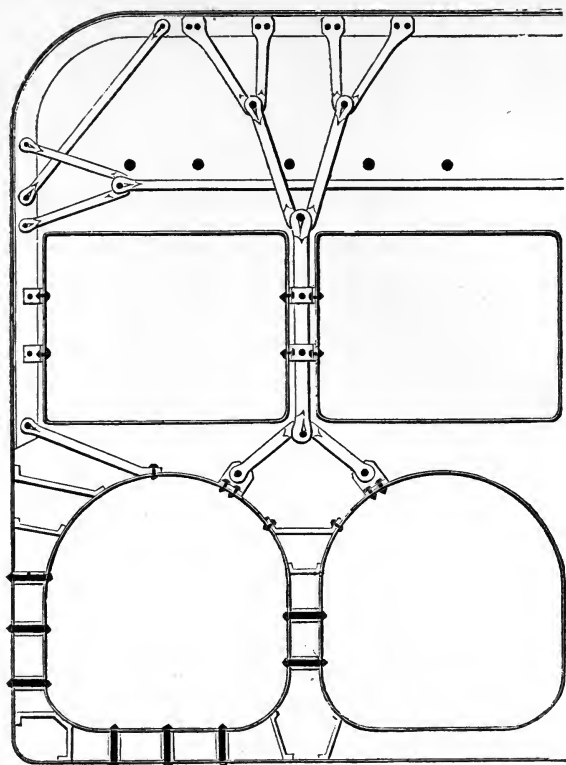


FIG. 4.—Showing the mode of bracing Marine Tubular Boilers.

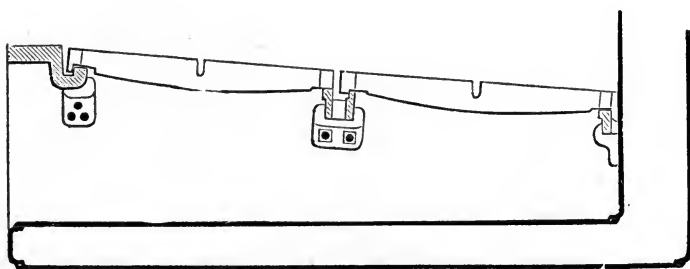
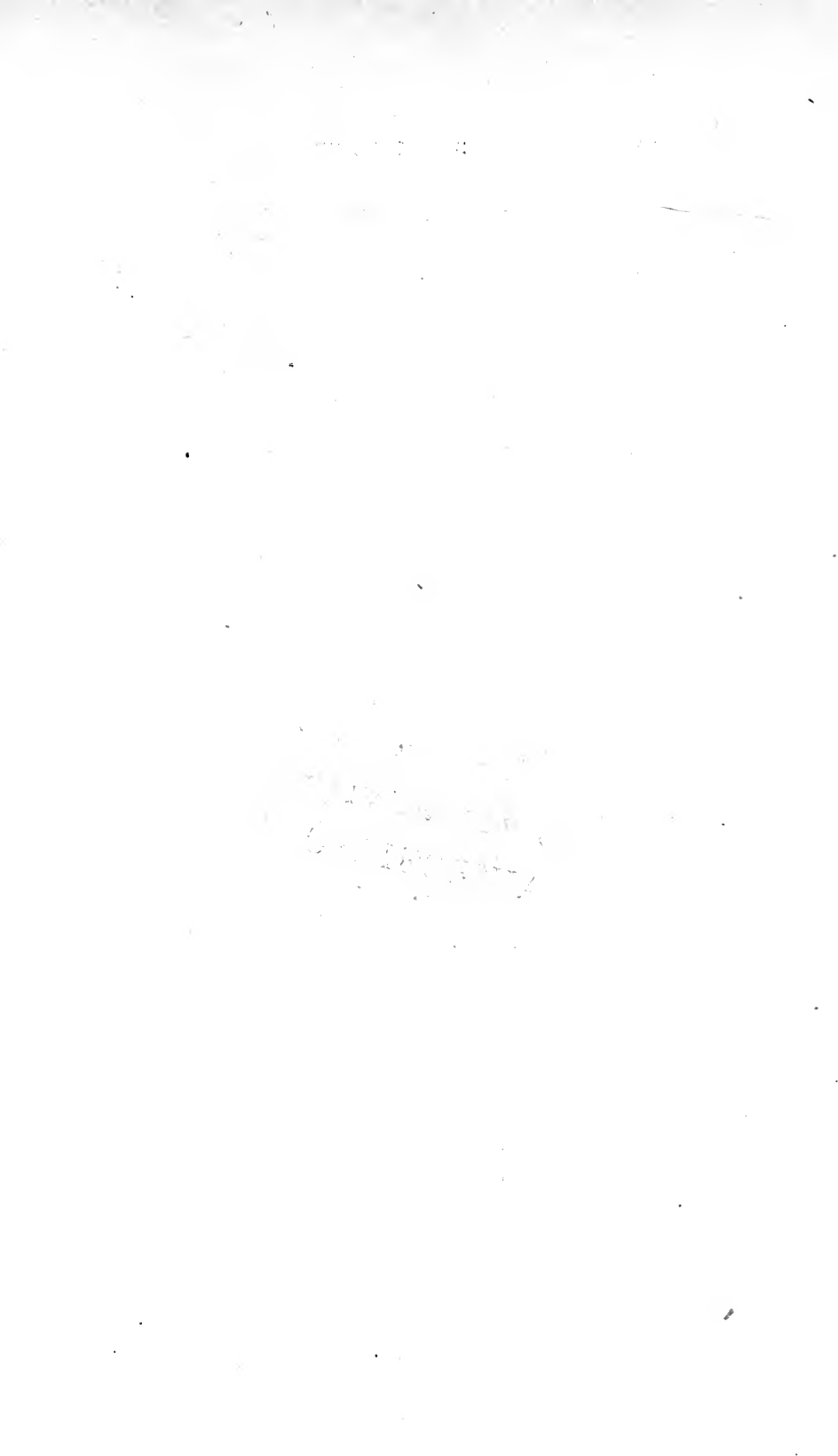


FIG. 6.—Grate-bars.



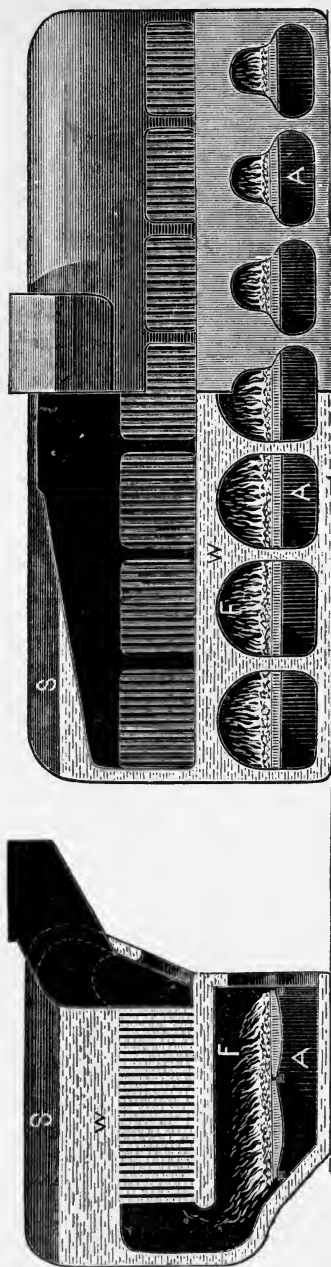


PLATE XXII.—Marine Water-Tube Boiler.

The amount of heating-surface of boilers of this class is to be estimated according to the general principle that all plates which serve to transmit heat from the furnace, or from the heated gases, to the water, are counted as heating-surfaces. In the boiler under discussion this includes the furnace, the tubes, and the front and back connections.

The boiler exhibited in Plate XXI. has the following dimensions: Shell, 27 feet 6 inches long, 13 feet 6 inches deep, 12 feet 1 inch high; number of furnaces, 8; number of tubes, 704; length, 7 feet; diameter, 3 inches; total heating-surface, 5,032 feet; aggregate area of tubes, 29 sq. feet; grate-surface, 160 square feet; diameter of smoke-pipe, 11 feet.

221. **Marine Water-Tube Boilers.**—Plate XXII., page 137†, exhibits a construction which differs from the marine tubular boiler only in the arrangement and functions of the tubes. In this boiler the tubes are vertical, and are water-tubes, connecting the water spaces above and below them. The flame and combustible gases pass among and around the tubes in their passage to the chimney; the heat being in this case applied to the external surface of the tubes.

There is no doubt that, considered merely in relation to the transfer of heat, this arrangement presents a better form than the fire-tube. The course of the heated gases among the tubes favors the absolute contact of the particles of gas with the surfaces of the tubes; the tubes acting as “baffles.” Moreover, it is conducive to the rapid transfer of heat to a fluid for the heat to be applied to the external surface of a tube while the *fluid* circulates within, and the vertical position of the tubes favors this liquid circulation. The arrangement permits also a less depth to the boiler, which is sometimes, in narrow vessels, an advantage.

Notwithstanding these apparent advantages, the vertical water-tube boiler, as shown, is now seldom used, and, in fact, it had but a brief existence after its adoption. The chief defects are, that when a leak occurs in a tube there is no possibility of stopping it except by drawing off the water; and even then it is difficult of access. If a leak occurs in a tube of the fire-tube or horizontal tube boiler, the ends of the tube, which are accessible, may be closed by plugs and the boiler used until repairs can be conveniently made. A leak in a fire-tube gives rise to no especial damage, except loss of water and steam; but a leak

from a water-tube may cause the gradual filling up of the interspaces between the tubes with salt, and thus impair the draft.

In estimating heating-surfaces, the *external* surfaces of the water-tubes are calculated.

The boiler of which Plate XXII. is a representation was constructed for the steam sloop-of-war Wampanoag, and had the following dimensions: Whole length, 24 feet 4 inches; depth, 9 feet; height, 9 feet 5 inches; number of furnaces, 8; total grate-surface, 126 square feet; total heating-surface, 3,028 square feet; draft area across tubes, 19.04 square feet; smoke-pipe, 15 square feet; water-tubes, 2 inches diameter; number of tubes, 2,000.

Experiments made on the evaporative qualities of these boilers by Mr. B. F. Isherwood, of the U. S. naval engineers, demonstrated that they were rather more efficient in producing steam than the fire-tube boilers.

Marine boilers of the classes just described require extensive bracing, and consequently have excessive weight compared with their evaporative powers. For this reason it is not usual to construct boilers of these forms for pressures of steam greater than 40 lbs., though a recent instance is given of such a boiler built for a steam-yacht being built to bear a pressure of 100 lbs. per square inch. For the higher pressures employed during the present day with the compound marine engines, the boilers are usually made of a cylindrical form, on the cylinder-tubular principle. Plates XXIII., Figs. 1, 2, 3 and 4, represent a pair of boilers made by English manufacturers for a large steamship furnished with compound engines, the shells being 11 feet in diameter, and the iron of the shell $\frac{7}{8}$ of an inch thick. These are becoming common in marine constructions, having the advantage of the greatest strength combined with the least material.

222. The Locomotive Boiler.—The locomotive boiler differs from the cylinder-tubular boiler in having but one system of tubes direct from the fire-box or furnace. Plate XXIV. represents the simplest form of a locomotive boiler, constructed for stationary purposes. While this cut represents all the essential parts of a locomotive boiler, it has not the exact form suitable for the railroad engine. The number and dimensions of the tubes in the railroad locomotive are greater, and in other respects the

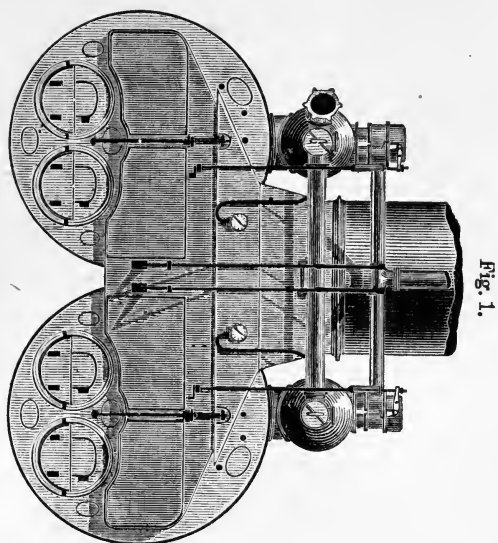


Fig. 1.

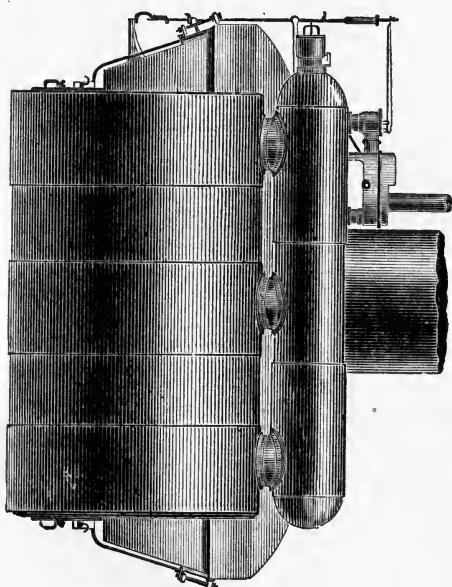


Fig. 2.

PLATE XXIII.—English Marine Tubular Boilers with Cylindrical Shells.

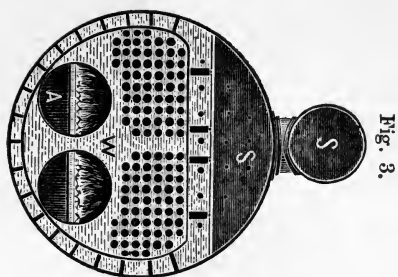


Fig. 3.

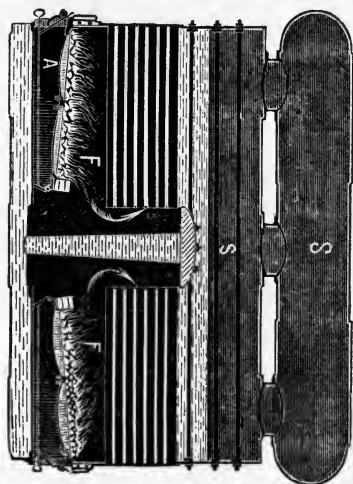


Fig. 4.

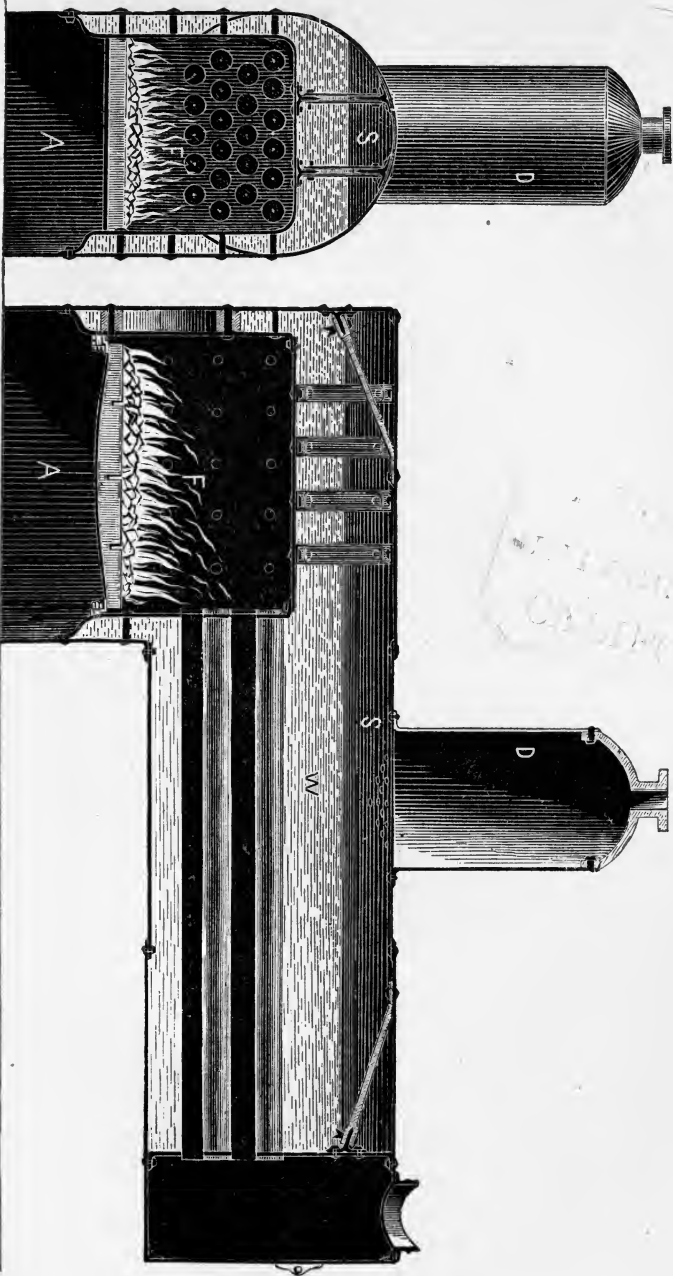


PLATE XXIV.—Locomotive Boiler.



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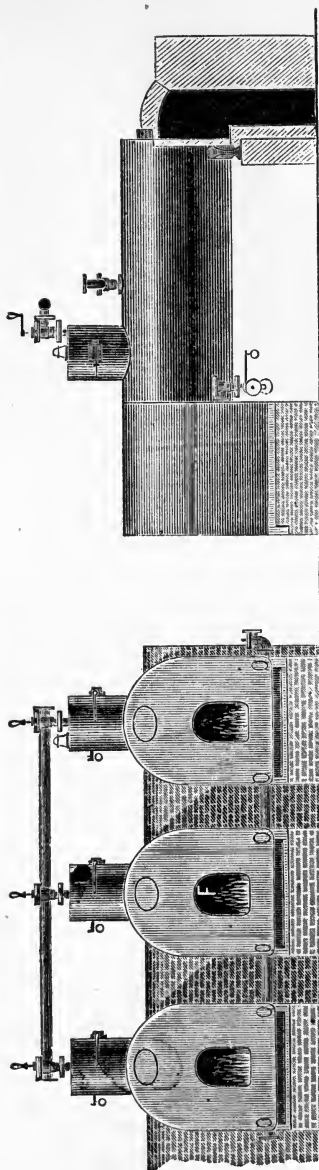
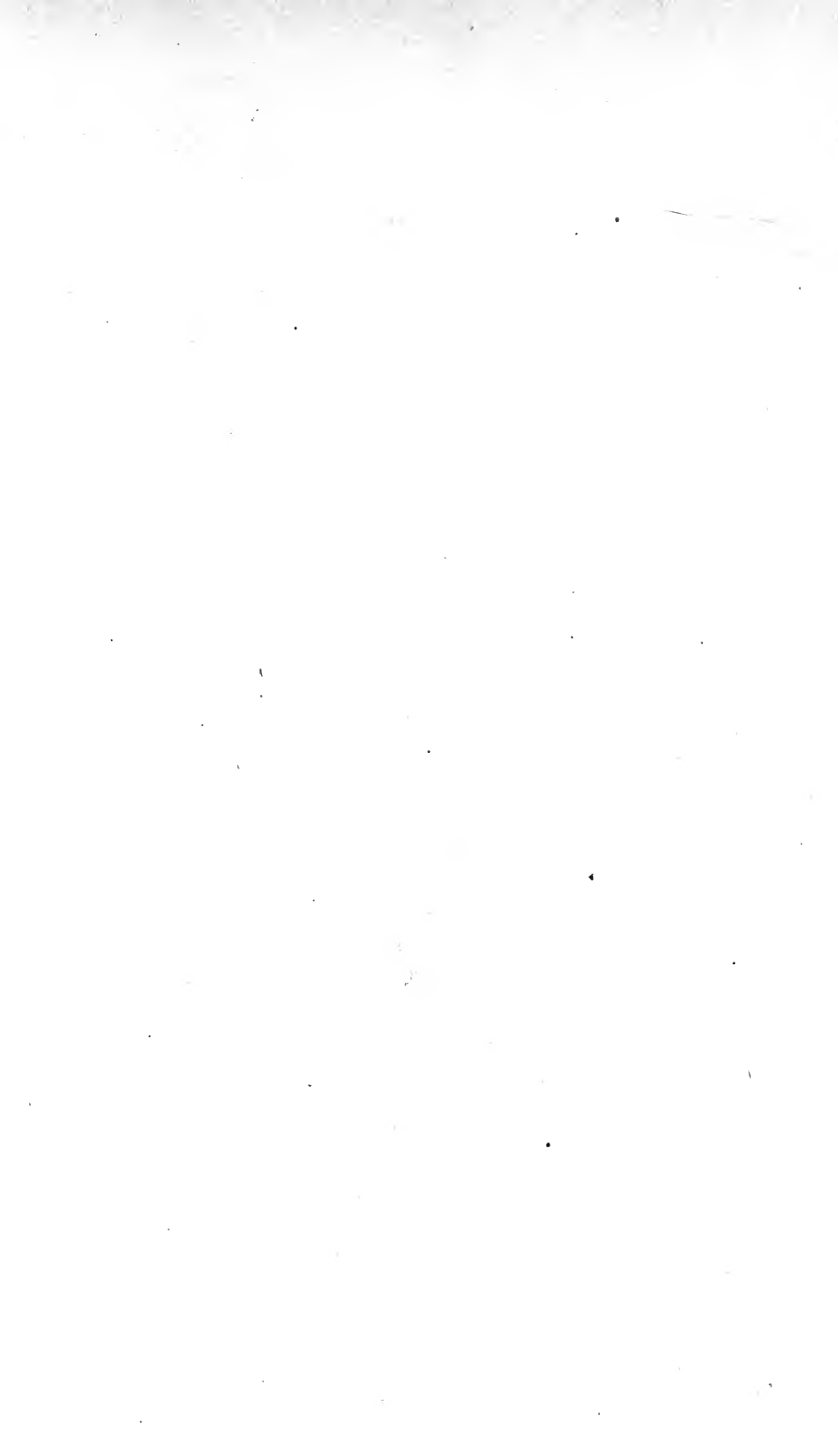


PLATE XXV.—Locomotive Boilers, connected for Stationary Purposes.



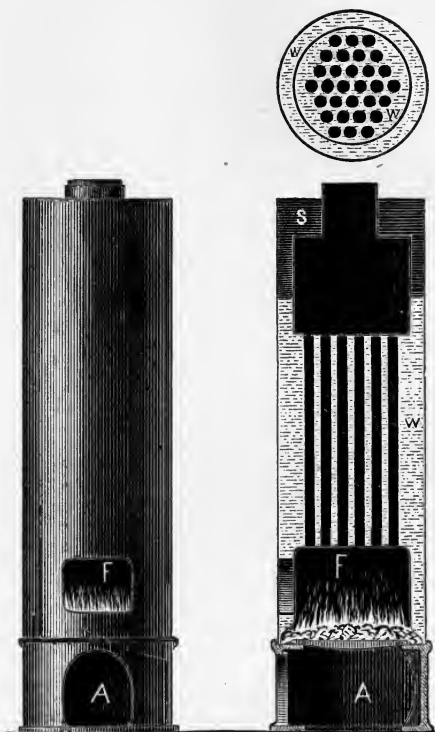


PLATE XXVI.—Upright Boiler.

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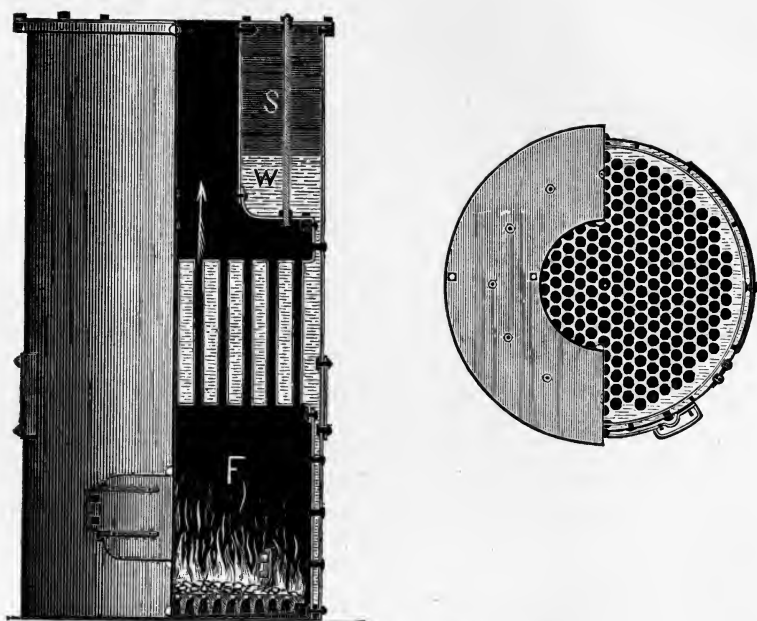


PLATE XXVII.—Fire-Engine Boiler.

railroad-locomotive boiler presents features peculiar to its adaptation to a particular purpose, but the essential parts of all such boilers are exhibited in the plate. The fire-box is rectangular in cross-section, and the tubes pass directly from the fire-box to the smoke-connection, or smoke-box.

It will be seen from the construction that the fire-box is an isolated chamber, separated entirely from the sides of the boiler, and surrounded by water. The sides and top being flat, and being subjected to external pressure, require to be strongly stayed to the shell. The crown-plate is stayed to the upper part of the shell, and the side-plates and shell are connected by sockets and bolts, the stays acting as struts as well as ties. The shell, dome, and tubes are constructed on the same principles as are applicable to the cylinder-tubular boiler. The heating-surface comprises the interior surface of the fire-box and the interior surfaces of the tubes. Plate XXV. represents a set of three locomotive boilers erected and connected for stationary purposes.

The locomotive boiler is the type of a large class of boilers, the distinctive feature of which is that the tubes pass directly from the furnace, or fire-box. For railroad engines various modifications are used, each establishment usually having a special form of construction. In some, a bridge and combustion-chamber are introduced, especially if the fuel is to be bituminous coal or wood. For a special description of the forms in general use in this country, the student is referred to the work of Mr. A. L. Holley on "American Railway Practice."

223. A modification of the locomotive boiler, much used for portable and stationary engines, is known as the *Upright Boiler*, an illustration of which is given in Plate XXVI. The simplicity of construction, convenience of access, and small space occupied by these boilers, combined with their evaporative qualities and strength, and combining, as they do, the chimney with natural draft with the upright shell, render them peculiarly adaptable for some conditions of use.

224. A form of this boiler, which demands special interest and attention, is found in the *Fire-Engine Boiler* represented in Plate XXVII. This is essentially an upright boiler of the locomotive type, but its peculiarity consists in the great number of tubes, and the great extent of heating-surface, compared with the cubic dimensions and the water-space. To facilitate

the sudden and quick raising of steam, the tubes are comparatively thin (usually made of brass or copper). This permits not only the introduction of a larger number in a given space, but the thinness of the tubes lessens the time for the first development of steam.

The cut exhibited, Plate XXVII., is from a drawing kindly furnished by the Amoskeag Manufacturing Co., of Manchester, New Hampshire. The dimensions of the boiler are as follows: Total height, 5 feet 4 inches; outside diameter, $31\frac{3}{4}$ inches; number of brass tubes, 301; diameter of tubes, $1\frac{1}{4}$ inch; length of tubes, 16 inches; distance from centre to centre of tubes, $1\frac{1}{2}$ inches; heating-surface, 157 square feet.

225. The following table gives useful proportions for the construction of cylinder boilers, cylinder-flue boilers, and cylinder-tubular boilers, and the quantities of water which the boilers of the dimensions enumerated will evaporate. These proportions are derived from current practice. In preparing the columns of evaporative capacities, an allowance of 25 per cent. has been made for differences of management, draft, and fuel, which may be met with, so that the evaporative capacities mentioned fall below the best practical results which may be obtained.

The evaporative powers are based on the supposition that coal is employed for fuel, and the draft is produced by a chimney of ordinary height, the combustion of fuel being about 9 to 12 pounds per hour on each square foot of grate-surface, and 1 pound of coal causing an evaporation of 7 to 9 pounds of water.

When steam in greater quantities than can be furnished by one of the largest of these boilers is required, two or more boilers may be used together.

226. Sectional Boilers.—In all types of boilers thus far considered, the water and steam space is either a single chamber, as in the plain cylinder boiler, or a chamber traversed by tubes, through which, in some cases, the heated gases find their way to the chimney, and in others the circulating water finds its way from one part of the water-space to another; the heated gases passing around the outside of the tubes. The volume of the water is large in proportion to the heating-surface, and the circulation of the water is not confined to prescribed channels.

TABLE. XXVIII.

Table showing the principal dimensions of boilers of the types named in the table, which have been found suitable in practice, and the water evaporated per hour by the same from the temperatures of feed-water of 60° and 160° F.

KIND OF BOILER.	DIMENSIONS.								WATER	
	SHELL OF BOILER.		FLUES OR TUBES.		STEAM DRUM.		GRATE SURFACE.	HEATING SURFACE.	Evaporated per Hour at 80 pounds Pressure from Tem- perature of	
	DIAM.	LN'TH	No.	DIAM.	DIAM.	HT			60°	160°
	Inch.	Feet.		Inch.	Inch.	Inch.	Sqr. ft.	Sqr. ft.	Lbs.	Lbs.
PLAIN CYLINDER BOILERS.	18	18.0			12	24	3.8	42	202	221
	21	21.0			14	28	5.3	58	280	306
	24	24.0			15	30	6.3	75	363	395
	27	27.0			16	32	8.6	95	458	501
	30	30.0			18	36	10.7	118	569	622
	33	33.0			20	36	13.0	143	689	754
	36	36.0			20	40	15.4	170	819	896
CYLINDER FLUE BOILERS.	24	8.5	2	6.5	12	24	3.3	56	200	219
	30	13.0	2	9.0	15	30	6.6	112	400	438
	36	16.0	2	11.0	18	30	9.9	168	600	657
	38	18.0	2	12.5	22	36	12.2	207	739	809
	40	20.5	2	13.5	24	42	14.8	252	900	985
	42	22.0	2	14.5	26	42	16.9	288	1028	1126
	44	23.0	2	15.0	26	42	18.4	313	1117	1224
	48	24.5	2	16.0	27	48	21.1	359	1282	1404
	52	26.5	2	17.5	28	48	24.9	423	1500	1654
	56	29.0	2	19.0	30	54	29.5	501	1789	1959
	60	31.5	2	20.5	32	54	34.5	586	2291	2092
	66	36.0	2	23.0	36	60	43.8	745	2660	2913
CYLINDER TUBULAR BOILERS.	22	6.5	18	2.0	12	24	2.9	80	187	205
	30	7.0	22	2.5	15	30	5.6	157	367	402
	36	8.5	34	2.5	18	30	8.2	229	536	586
	40	9.0	42	2.5	22	36	10.5	294	688	753
	44	11.0	40	3.0	24	42	14.7	409	957	1047
	47	12.5	34	3.5	26	42	16.6	466	1090	1193
	51	14.0	34	4.0	28	48	21.1	592	1385	1516
	55	14.5	42	4.0	30	54	26.5	742	1736	1900
	60	15.0	52	4.0	34	54	32.2	931	2178	2383
	66	15.0	60	4.0	36	60	38.3	1072	2508	2744
LOCOMO- TIVE BOILERS.							3.0	85	199	218
							5.9	165	386	422
							8.8	245	573	627
							11.4	320	749	819
							14.3	400	936	1024
							17.1	480	1123	1229
							22.5	630	1474	1613
							27.7	775	1814	1984

Moreover, an external shell is necessary, which must contain the water and steam, and generally, also, the system of tubes: this

shell being subjected to the whole effect of the steam pressure.

A system of construction which has come largely into use of late years, and which is becoming more and more advanced towards perfection in its mechanical details, is known in this country by the name *Sectional Boilers*, and in France, boilers with *rapid circulation*, or *water-circulating boilers*. This system may be said to have originated with Mr. Jacob Perkins, who, in 1831, obtained a patent in England for improvements in generating steam, in which he insisted on the advantages to be gained by causing the water to circulate rapidly over the heating-surfaces exposed to the direct action of the fire. In 1839 Perkins obtained a patent for a more complete apparatus involving this idea, under the title, "Apparatus for Transmitting Heat by Circulating Water." Steam generators constructed with special reference to this idea were extensively tried, but were finally abandoned for the reason that, owing to practical difficulties in their construction, the high pressures employed, and the difficulty of keeping them in repair, they soon became unfit for use, and it is only from a comparatively recent date that they have again come into use under more favorable auspices.

The *Sectional Boiler* consists essentially of a system of tubes so arranged that a continuous circulation of the water is maintained through the tubes from the mechanical action arising from some portions of the tubes being maintained at a higher temperature than others, the heated and lighter water ascending and the cooler and heavier water descending. The shell is dispensed with and the heat applied directly by both radiation and contact to the exterior surfaces of the tubes. The steam-space is usually a large tube or a system of tubes with which the various *sections* of tubes are connected, and the various devices which are found in practical use for connecting and arranging the tubes, so that they shall form a compact arrangement with all the necessary conditions for applying heat, for accessibility, and for promoting circulation, constitute the *sectional boilers* of the present day, which usually take their names from the inventors or manufacturers.

The most successful constructions in this country are those known as the ROOT BOILER, the ALLEN BOILER, and the PHLEGER BOILER. Plates XXVIII. and XXIX. represent the Root

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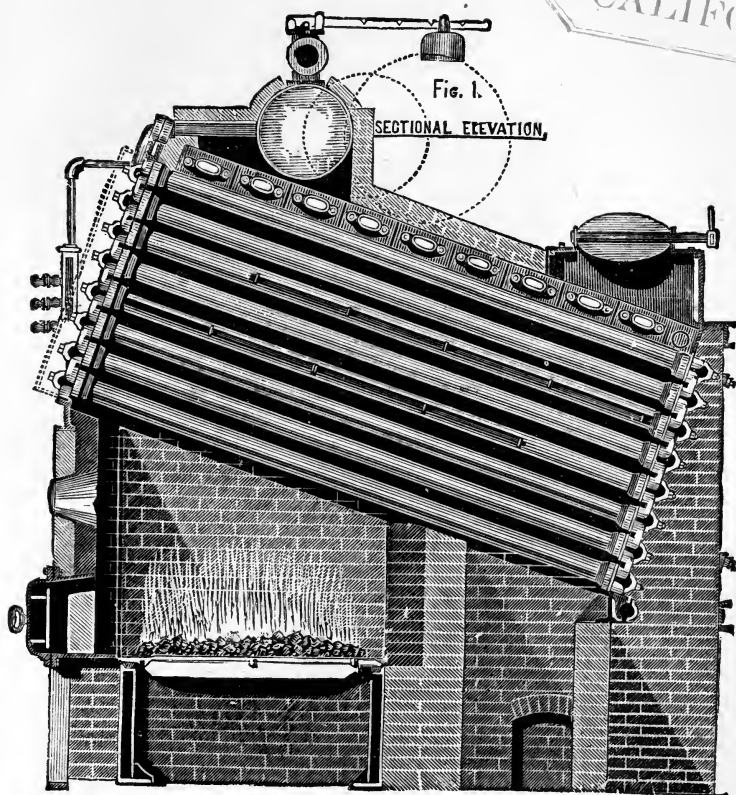


PLATE XXVIII.—The Root Boiler.

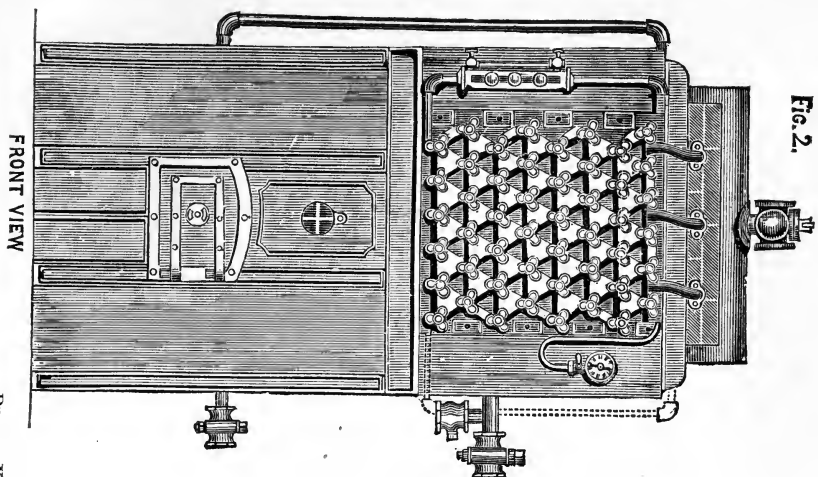
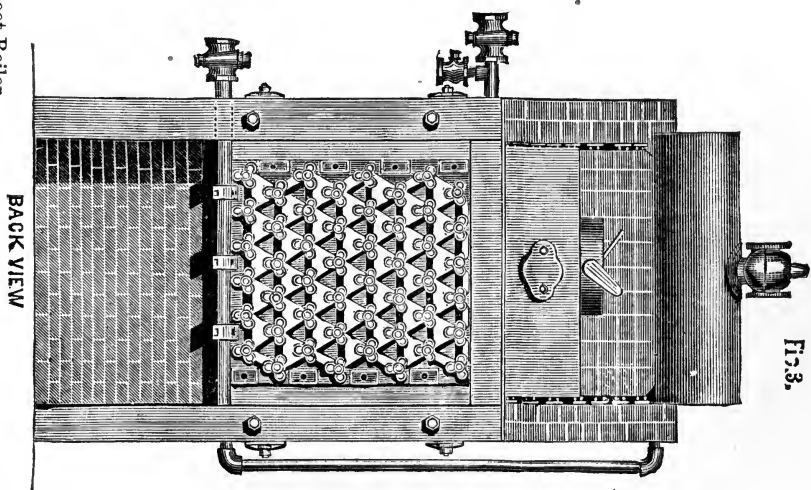


PLATE XXIX.—The Root Boiler.



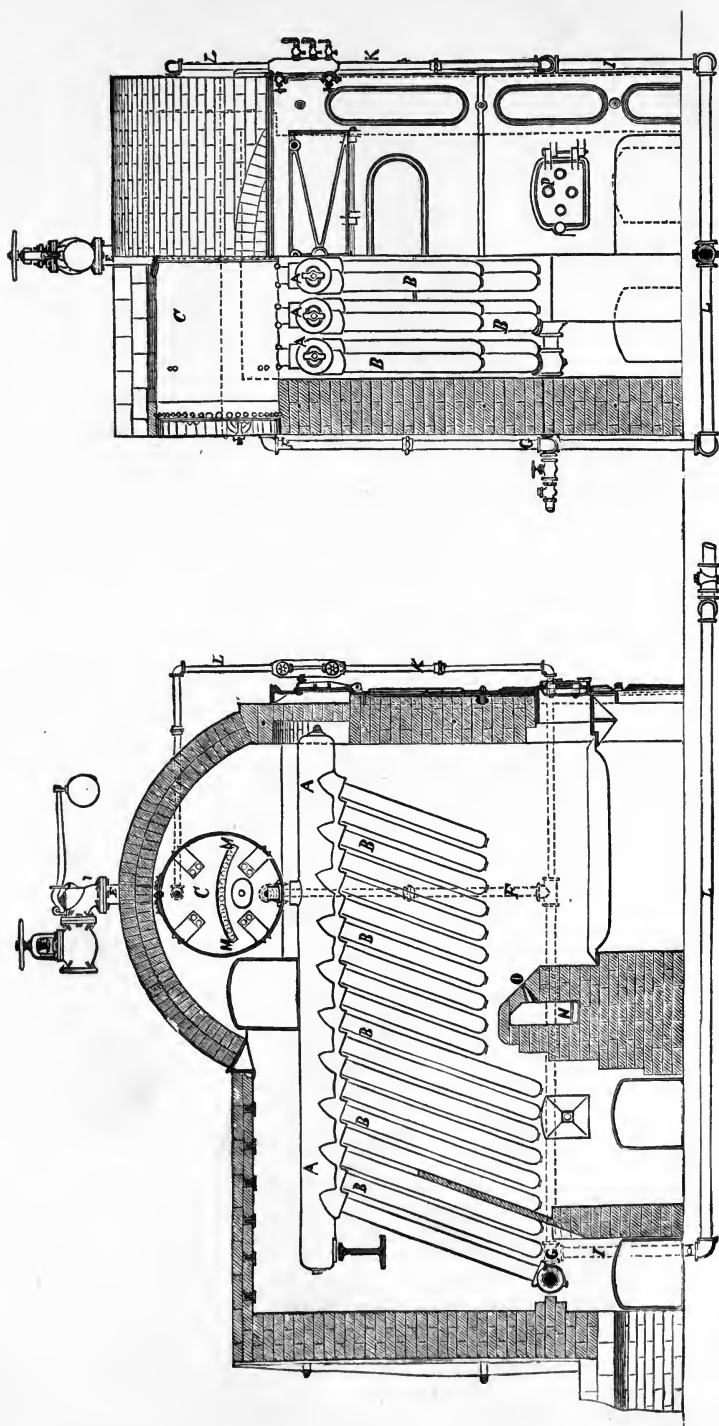


PLATE XXX. —The Allen Boiler.

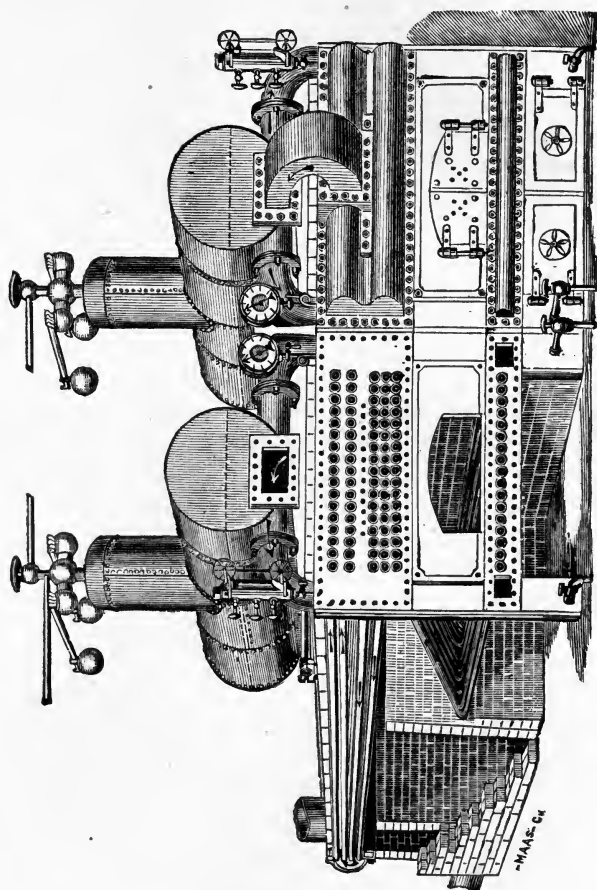


PLATE XXXI.—The Phleger Boiler.

drum is connected with another, D, $2\frac{1}{2}$ feet in diameter and 8 feet long. (This drum has been omitted in the engraving.) From this latter drum the steam leaves the boiler by the pipe E. These drums are so arranged as to superheat the steam, being surrounded by the products of combustion; and in the bottom of each of the drums are pipes, F, G, connecting with H, the lowest point of the boiler, to allow the water carried over by the steam to drain back. The feed and the water gauge and gauge-cocks are connected to the steam and water spaces by the pipes J, K, L, leading to the steam-drum, C, and the cross-connection, H, respectively. The wrought-iron pipes are connected to the cast-iron cylinders at an angle of 20° from the vertical, the inventor claiming that as the most effective position. The inventor also claims great facility for making repairs by merely unscrewing a defective tube and substituting a good one.

DESCRIPTION OF THE PHLEGER BOILER.

229. This consists of a number of wrought-iron tubes, connected to cast-iron tube-plates, and set in brick-work. There are 17 bent tubes, A, each 2 inches in diameter and 15 feet long, so arranged as to form the furnace and a "water-grate," being secured at the ends to cast-iron tube-sheets, S, S'. There are, also, 68 straight tubes, of the same dimensions, secured at the ends to tube sheets, S, S'. These tubes are all connected with each other and the steam-drum, D, by a series of cast-iron caps or water-ways, C', C'', C''', and by the pipes, S P, S P', these latter being flanged, and secured to the tube-sheets by bolts. The steam-drum is of wrought iron, and has a diameter of $2\frac{1}{2}$ and a length of 12 feet, and contains shelves, L, L, for the purpose of preventing foaming.

In France the boilers of M. Belleville, constructed on similar principles, enjoy, perhaps, the highest reputation, though many others of the same character have been successfully introduced.

230. Plate XXXIV. represents a sectional boiler of a construction quite different from all others which come under this denomination. It is called the *Harrison Boiler*, and is the invention of Mr. Joseph Harrison, of Philadelphia. The sections are composed of hollow cast-iron spheres or globes connected together and communicating freely with each other. This form combines, according to the design of the inventor, the greatest strength with the least weight of costly material.

Sectional boilers have evaporative powers not inferior to

Boiler; Plate XXX. represents the Allen Boiler, and Plate XXXI. the Phleger.

The following description of these boilers is taken from the report of a committee appointed by the American Institute to test these boilers, at the exhibition of the Institute in 1871. The committee consisted of Professor Thurston, of the Stevens Institute of Technology, Messrs. Robert Weir and Thos. J. Sloan, whose experimental tests will be referred to in another place.

DESCRIPTION OF THE ROOT BOILER.

227. This boiler consists essentially of 80 wrought-iron tubes, each 4 inches in diameter, and 9 feet long. These tubes are set in brick-work, at an angle of about 30° from the horizontal. The tubes are connected together by the system of triangular plates and crowfeet represented in figures 1 and 2; the joints being formed by the aid of rubber grommets. The boiler has a steam-drum, 18 inches in diameter, and $6\frac{3}{4}$ feet long. The superheating of the steam is effected in the upper portion of the boiler, where the tubes are, like those forming the water-space, surrounded by the heated gases. The water was maintained, during the trial, just above the fourth row of tubes.

The inventor claims that by the contraction of the passages, caused by the method of connecting the tubes, the steam is disengaged from the water in a comparatively dry state.

The areas of heating and grate surfaces of this, and of all the boilers under consideration, are given in the table of results.*

DESCRIPTION OF THE ALLEN BOILER.

228. This boiler possesses several novel features. There are 9 cast-iron cylinders, A, A, A, etc., each 7 inches internal diameter, and 11 feet long; and into each of these cylinders 18 wrought-iron tubes, B, B, each $3\frac{1}{2}$ inches in diameter, and closed at one end with plugs, are screwed. In each section of wrought-iron tubes, 9 of the tubes have a length of 3 feet and 2 inches, and the remaining 9 have a length of 4 feet and 5 inches each. The sections are all connected by the cast-iron cylinders to a steam-drum, C, 2 feet in diameter and 8 feet long; and this

* The total of all surfaces exposed to contact with the products of combustion is taken as heating-surface.

those of the other types, and possess the especial advantages of occupying less space and of being safe from explosions. The want of durability which characterized the earlier constructions has been remedied, to a great extent, by improved modes

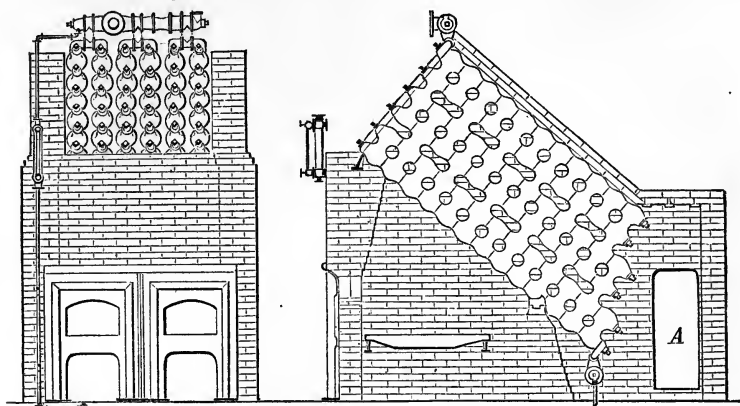


PLATE XXXIV.—Harrison Boiler.

of construction, at least for stationary purposes. One disadvantage connected with them consists in a liability to rapid fluctuations of pressure if steam is drawn from them in largely varying quantities in short intervals of time, the volume of water contained in the boilers being small compared with that of other types. For marine purposes, when salt-water is used, deposits are apt to be formed, which are removed with difficulty, and they have not yet been applied to any extent in marine constructions.

231. It will be seen from the above descriptions, that while the same general principles of combustion and of the transfer of heat control the detailed construction of steam generators, adaptation to special uses is the consideration which gives rise to many varieties of external forms.

The character of the combustible has an influence on the proportions of parts, and often requires special consideration. This is peculiarly the case where the combustible is entirely gaseous. When the gases to be burned are drawn from blast-furnaces, and are led by conduits to the ignited coals of a grate, the ordinary disposition of the parts of the boiler may be followed. When the gas is burned alone, the grate may be suppressed.

The gas from blast-furnaces may be utilized not only by employing the heat of the gas, but also in burning the oxide of

carbon, of which it is in part composed. In burning this gas it is not necessary to furnish air in so great a quantity, and the construction of the furnaces is thus further simplified. One boiler is often placed in such a manner as to consume the gas from several furnaces.

In the metallurgical establishments of Creusot and Oullins, in France, the boilers for utilizing the furnace-gases are vertical cylinder boilers placed in a chimney lined with fire-brick.

Boilers somewhat similar to the locomotive boiler are also used in France for the same purpose. In England, vertical cylinder boilers of large diameter with interior flues are used; each boiler receiving the heated gases from several puddling furnaces.

In all cases where the gas is not burned, the problem consists in devising the best mode of conducting it in contact with the greatest amount of heating-surface; and where a partial combustion also takes place in the boiler, the necessary means of continuity of combustion by a bed of ignited coals must be provided; and with these conditions must be combined the fundamental requirements of durability and safety.

NOTE.—*Boilers with forced circulation.* In all steam generators thus far described, and in all others as at present used, the circulation of the water within the boiler is produced by a difference of specific gravity of the heated water at different points, aided perhaps by the rising of bubbles of steam. The circulation is dependent on the evaporation, as soon as a constant working pressure is reached, and is necessarily slow. I have made experiments, assisted by Messrs. T. W. Mather and J. K. Klein, graduate students of the Sheffield Scientific School, to determine the efficiency of a *forced circulation* of the heated liquid. The difficulty of constructing very small steam generators having sufficient strength to resist great pressure, and at the same time a high rate of evaporation with reasonable economy, has long been recognized. On account of this difficulty the use of very small engines is limited. The boiler in such engines must have such large proportions relatively to the engine that it ceases to be an economical apparatus.

The object of my experiments was to reduce the heating-surface, and at the same time make it *more efficient* by a forced and continuous circulation of the water in the boiler, through the means of a circulating pump. Various combinations and modes of circulation have been tried, with results which thus far appear conclusive. A steam generator of very small volume and weight made of coils of gas-pipe and consequently having a resistance of several thousand pounds per square inch, has been made to evaporate quantities of steam per hour which by ordinary processes would require a boiler of very much greater volume. The principle of *forced circulation* has not heretofore been employed for this purpose, but there is reason to believe that it may become practically useful, especially for solving the important problem of very small steam-engines—engines having but a fraction of a horse-power.

CHAPTER VI.

THE CONSTRUCTION OF STEAM GENERATORS.

232. WHATEVER may be the type of steam generator selected for a special purpose, the following fundamental considerations are involved in its design and construction :

I.—*Proportion of parts.*

II.—*Actual dimensions.*

III.—*Kind, quality, and strength of the materials employed, and the mechanical conditions of the structure.*

The proper proportions of the parts determine the economy or efficiency of the apparatus.

On the actual dimensions depends the capacity for producing steam, or, as it is sometimes expressed, the *power* of the boiler ; and on the kind, quality, and strength of the materials employed, and the mechanical perfection of the structure, depend not only the first cost, but also the strength of the structure and its durability.

233. *Proportion of Parts.*—The parts of which the relative proportions require special consideration, are those which determine the *combustion of the fuel* and the *transfer of heat*.

It is obvious that the first object to be attained is the thorough and complete combustion of the fuel. If any combustible gases or any portion of the fuel in the form of smoke escape from the chimney, a direct loss occurs, which should be prevented if possible. This question may be discussed without reference to the question of transfer of heat, in which the proportion of heating surface is chiefly to be considered ; and the elements on which the discussion depends are those parts of the apparatus which control the introduction of air to the fuel, and the quantity and disposal of the fuel with which the air comes in contact.

234. *Chimneys*.—The chimney, in all cases in which the draft is produced by a simple “chimney-draft,” performs the functions of a machine, and its dimensions (its height and cross-section), taken in connection with the area of the grate, and the surface of contact of the fuel exposed to the action of the air, are the principal elements on which not only complete or perfect combustion, but the quantity of fuel burned in a given time, depend. In boilers provided with any other means of draft, such as the steam jet, or the blower, the dimensions of the chimney are not so important. In almost all stationary, and in nearly all marine, boilers, the draft is produced solely by a chimney, which forms an indispensable and important part of the apparatus. The determination of the proper proportions between the heating surface and the grate surface depends on the initial temperature of the gases; and as the initial temperature varies with the rate of combustion, or the height of the chimney, the height of the chimney indirectly enters into the consideration of this proportion.

It is well known that the draft of a chimney is caused by a difference of pressure at the base of the chimney, acting in an upward direction, due to the difference between the weight of the heated gases in the chimney, and a column of equal height and cross-section of the external air. This difference of pressure is easily found. If we take a unit of area of the cross-section—one square foot for instance—the weight of the column of external air will be the height of the chimney multiplied by the density of the external air, and the weight of the column of heated gases, of equal height, will be equal to the height of the chimney multiplied by the density of the *heated gases*. If h be the height of the chimney, D the density of the external air, and D' the density of the heated gases, the difference of pressure referred to will therefore be, in algebraic symbols,

$$p = h D - h D' = h (D - D')$$

This unbalanced pressure acts as a motive force to drive the heated gases through the chimney and out at the top. In order to find what height of column of the external air would produce this pressure, acting simply by its weight, we have to divide the pressure by the density of the external air, and will have—

$$\frac{p}{D} = H \left(\frac{D - D'}{D} \right)$$

It is a well-known law of dynamics that the theoretical velocity with which the air would enter the chimney, if there were no resistance, would be found by the equation,

$$H \left(\frac{D - D'}{D} \right) = \frac{v^2}{2g}$$

from which the theoretical velocity of access of external air would be

$$v = \sqrt{2gH \times \left(\frac{D - D'}{D} \right)}$$

The values of D and D' may be readily found from principles already enunciated. If D_0 represent the density or weight of a cubic foot of air at 32° and at atmospheric pressure, given on page 66, the weight at any other temperature will be $D = D_0 \times \frac{T_0}{T_1}$, T_1 being the temperature of the external air generally higher than T_0 , the absolute temperature of melting ice.

If the external air be, for instance, at 60° F., T_1 will be $459.4 + 32 + 60 = 551.4$, absolute temperature. D_0 , found from the table on page 66, is .08073. $T_0 = 459.4 + 32 = 491.4$: from these given quantities,

$$D = 0.0873 \times \frac{491.4}{551.4} = 0.07182$$

For the weight of a column of the heated gases of the chimney, having a base of one square foot, a similar process is to be followed. The chimney gases being composed of nitrogen, oxygen, and carbonic acid, principally, it is necessary to ascertain first the proportions of each of these gases in a cubic foot, at atmospheric pressure and at the temperature of the heated gases. Results of experiments made by Combes, Johnson, and others, indicate that these gases are found in the products of combustion in the following proportion, nearly, when the fuel is ordinary coal. The proportions in one cubic foot are:

Carbonic acid.....	0.10
Nitrogen.....	0.79
Oxygen.....	0.11

These proportions are adopted by Morin and Tresca after comparing the results of various experiments. At 32° F. and atmospheric pressure, one cubic foot of the heated gases would therefore weigh, according to the table, page 66—

Carbonic acid.....	.10 × .12344 = 0.01234
Nitrogen.....	.79 × .07860 = 0.06209
Oxygen.....	.11 × .08926 = 0.00981

Weight of one cubic foot..... = 0.08424 lbs.

If we suppose the temperature of the heated gases to be 500° F., the density ρ' at 500° will be

$$0.08424 \frac{T_0}{T_2} = 0.08424 \times \frac{491.4^\circ}{459.4^\circ + 32^\circ + 500^\circ}$$

The velocity v determined from this formula is not, however, that with which the external air will enter the chimney. Resistance is offered to the passage of air through the grate, through the bed of fuel, and through the flues and chimney. These resistances do not admit of theoretical determination, and can only be found by direct experiment. They are proportional to the square of the actual velocity, and depend on the diameter and length of the flues and chimney, the thickness of the bed of fuel, and the state of division of the fuel.

The experiment of Peclèt led him to propose the formula for the actual velocity essentially as given below :

$$v' = \sqrt{2 g H \left(\frac{\rho - \rho'}{\rho} \right)} \cdot \sqrt{\frac{1}{1 + A + \frac{K}{d} L \left(\frac{T_2}{T_1} \right)^2}}$$

In the formula of Peclèt he supposes the air to enter the chimney at 32° F., and the density of the heated gases to be

the same as that of air at the same temperature, so that his formula is:

$$v' = \sqrt{2 g H \left(\frac{a t}{1 + a t} \right)} \sqrt{\frac{1}{1 + R}}$$

(a) in this formula being $\frac{1}{273}$, and t the temperature Cent. of the heated gases.

For heights of 10, 20, and 30 metres, he finds for the ordinary condition of chimneys of manufacturing establishments: $R = 29.98$, 33.49 , and 38.29 , and $v' = .18$ v. $v' = .17$ v. $v' = .16$ v.

In Peclèt's formula κ represents a coefficient of friction, L and d the length and diameter of the chimney and flues, and A a coefficient of resistance of the grate.

The values of the velocity of access of air found by Peclèt for heights of 10, 20, and 30 metres, or 32.8 feet, 65.6 feet, and 98.4 feet, were 5.1 feet, 8 feet, and 9.18 feet per second, or 18,360, 28,800, and 32,948 feet per hour. These velocities, divided by the number of cubic feet of air required to burn one pound of fuel, will give the quantity of fuel burned per hour for each square foot of section of the chimney, the section of the chimney being supposed equal to the free surface of the grate. The volume of air required to burn one pound of fuel of a given kind is given in the table page 93. In the ordinary process of combustion in a grate, it is apparent that some of the air which enters must escape contact with the fuel, and enter the chimney as air. The quantity which thus escapes has been usually assumed equal to the quantity which is required for combustion, or, in other words, the quantity which enters the furnace has been estimated to be double the quantity required for combustion.

This was the deduction usually made from the experiments made by Prof. W. R. Johnson, Peclèt, and by a commission appointed by the English Board of Admiralty. But more recent experiments, especially those made by the Industrial Society of Mulhouse, indicate that this is too large an allowance, and it is stated by Morin and Tresca as the result of the examination of all the experiences on the subject, that about one and seventy-five hundredths of the amount actually required for combustion appears to be nearer the true amount to

be allowed. This corresponds to the composition of the heated gases which has been already given. According to this result, the quantity of air actually drawn into the furnace for each pound of fuel burned will be about 250 feet. The consumption of fuel per square foot of section of the chimney will then be, for the heights above given, viz. :

Heights,	32.8	65.6	98.4
Pounds,	73.4	115.1	137.8

If it be assumed that each square foot of section of the chimney corresponds to 8 square feet of grate surface, the above figures will give for the rate of combustion on each square foot of grate surface,

Pounds,	9.2	14.8	17.2
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These results seem to be the nearest that can be attained by combining theoretical considerations with experimental deductions. The conditions which exist in different chimneys and furnaces in regard to the resistances are so complex and various that no theoretical formula will give results which can be considered even approximately correct. A comparison of the results obtained by the partly empirical formula of Peclèt, applied to ordinary conditions of practice, with numerous examples, in which the quantity of fuel burned and the dimensions of the chimneys are given, has led to the suggestion of the following practical table of heights, and quantities of fuel burned per square foot of section of the chimney per hour. This table is intended only to give approximate quantities, and although instances are given which differ from the table considerably, it is to be borne in mind that in constructing a chimney an excess of height should be chosen, since the draft may be afterwards regulated by a damper, and no serious error in choice is likely to occur.

The diameters at the top suitable for the given heights may be estimated from 1 foot for the least height, to 4 feet for the greatest.

This table was constructed by collecting reliable data from experiments, and plotting the heights corresponding to the rate of combustion found. A curve drawn through the mean posi-

tions furnished the means of interpolating the figures in the table.

TABLE XXIX.

Showing heights of chimneys for producing certain rates of combustion per square foot of area of section of the chimney.

Heights in Feet.	Pounds of coal burned per hour per square foot of section of chimney.	Pounds of coal burned per hour per square foot of grate, the ratio of grate to sec- tion of chimney being 8 to 1.
20.....	60	7.5
25.....	68	8.5
30.....	76	9.5
35.....	84	10.5
40.....	93	11.6
45.....	99	12.4
50.....	105	13.1
55.....	111	13.8
60.....	116	14.5
65.....	121	15.1
70.....	126	15.8
75.....	131	16.4
80.....	135	16.9
85.....	139	17.4
90.....	144	18.0
95.....	148	18.5
100.....	152	19.0
105.....	156	19.5
110.....	160	20.0

It appears from the table that a difference of height of 8 feet corresponds to a difference in rate of combustion of about one pound per square foot of grate surface, the ratio of the grate to the chimney section being 8 to 1.

This result was verified in particular cases as approximately true.

The quantities given in the table refer to the average conditions of chimneys of steam generators.

235. *Grate Surface.*—The height of the chimney, taken in connection with the temperature of the heated gases, determines,

as has been shown, the rate of combustion. This is true only when the fuel is so disposed as to insure complete or perfect combustion. If air, after having come in contact with incandescent fuel, and after the oxygen combines with carbon to form carbonic acid, comes again in contact with fuel at a lower temperature, the carbonic acid usually parts with a portion of its oxygen, and carbonic oxide, which is a highly combustible gas, is formed and passes off by the chimney. The combustion will then be incomplete. The fuel must therefore not only be in just sufficient quantity, but it must be properly disposed.

In practice it is spread over a grate to the depth of 7 to 10 inches, and the grate is made to bear a certain proportion to the section of the chimney.

By free surface of the grate is to be understood the openings between the grate bars, further diminished as they are in area by the stopping of the passages by the lumps of fuel.

It is usual to make the openings between the bars $\frac{1}{4}$ to $\frac{2}{5}$ of the whole area of the grate surface. If these openings are insufficient, there will be a deficiency of air and incomplete combustion will result.

The proportions of the grate, section of chimney and flues, and the heating-surface, are generally given in terms of the grate surface, which is assumed as unity. The grate being 1, the following proportions have been found to answer in practice for the free spaces between the grate bars:

Plain cylinder boiler.....	0.25.
Cornish boiler.....	0.23
French boiler.....	0.34
Tubular and flue boilers.....	0.40

These numbers, multiplied by the total area of the grate surface, will give the total area of openings between the bars. For burning bituminous coal or wood it is usual to add openings to the amount of about $\frac{1}{8}$ th of the area of the grate by holes through the furnace doors.

Such additional apertures are sometimes placed behind the bridge, and air is often forced into the furnace by a steam jet, to complete the combustion and prevent smoke.

There does not seem to be any uniformity of practice in regard to the proportion between the total grate surface and the

cross-section of the chimney, or the draft area over the bridge walls.

According to the experiments of Mr. Isherwood, the best proportion for the draft area is $\frac{1}{3}$ of the area of the grate. Many constructors, however, make it greater, amounting in some cases to $\frac{1}{2}$ and $\frac{1}{4}$. Others make it less, $\frac{1}{10}$ being not uncommon. The proportion will be assumed as best at $\frac{1}{3}$, the thickness of the bed of fuel being, under these conditions, about 7 inches. The cross-section of the chimney may have the same proportion, though the section of the chimney at the top is generally less than at the base. The cross-areas of the different sets of flues generally diminish, also, in going towards the chimney.

236. *Heating Surfaces*.—The heating-surfaces of a boiler have already been defined to be all those surfaces, or *plates*, of the boiler which serve to transmit heat from the furnace or heated gases to the water or steam within the boiler. From the laws of transfer of heat it appears that the quantity of heat transmitted by any surface depends on the extent of the surface, and the difference of temperature between the source of heat and the absorbent; or, in the case of steam generators, the difference in temperature of the incandescent fuel, or heated gases, and the water in the boiler.

The arrangement, or disposition, of the heating-surfaces has been already given in the descriptions of the various types of boilers. The extent or amount of heating-surface is fixed with reference to the initial temperatures of the furnace and gases; or, since these temperatures are proportional to the rate of combustion, the extent of heating-surface will depend on the rate of combustion to be employed. The extent of heating-surface must evidently also be in proportion to the absolute quantity of fuel burned in a given time, or, what is the same thing, it must have a direct relation to the grate-surface.

To illustrate this clearly, in the following diagram, Fig. 7, let o r represent a flue or tube having an extent of heating surface from the initial point o to the right, o r , equal to the heating surface of a given boiler, not taking into account the surface exposed to direct radiation; the point o being the entrance to the flue. With a given rate of combustion let o A represent the initial difference between the temperature of the heated gases and the water in the boiler, the temperature of the latter being constant. The curve A b , drawn according to the

law of diminution of temperature, will represent the curve of temperatures; at the point b we may suppose the temperature to have been reduced to about 600° F. Suppose now a different and higher rate of combustion to be maintained, the initial difference in temperature may be represented by $o A''$ and the curve $A'' b''$ will represent the curve of temperature corresponding to this higher temperature. It is evident from the diagram, that to reduce the temperature of the heated gases to the *same final temperature*, 600° , the heating surface will have to be extended to f' . And for another and higher rate of combustion, the initial difference of temperature being $o A'''$, the heating surface will have to be extended to f'' .*

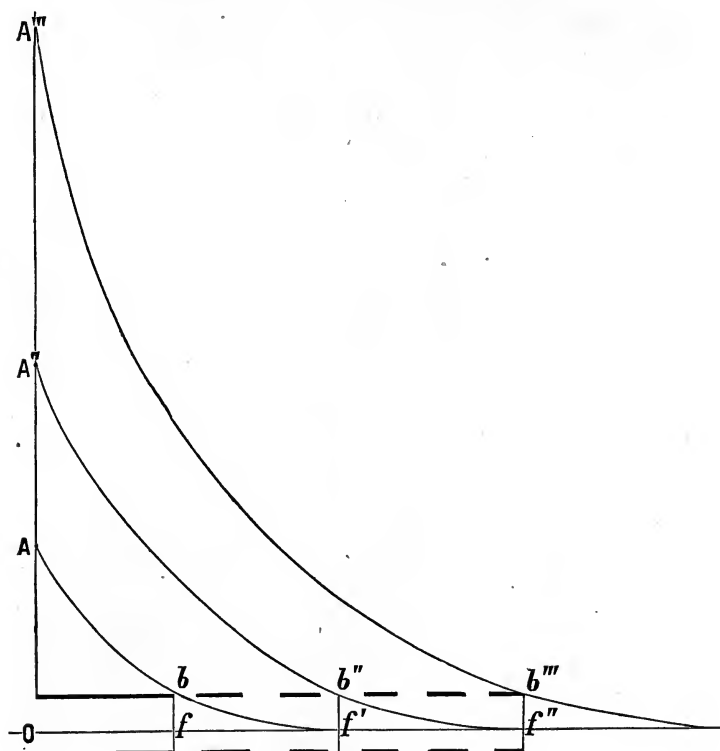


Fig. 7.

* This increase in practice is not generally made by extending the heating-surface in the direction of the chimney, but by enlarging the cross-section.

The curves showing the variations in the quantities of heat transferred may be found from the curves of temperature by taking the value of any ordinate of the curve of temperature and raising it to the power whose index is 1.233 according to Dulong and Petit, or to the second power, according to Rankine, and the total quantities of heat transferred through the heating-surface will be represented by the areas included between the axis of x , the curves of quantities of heat, and the extreme limiting ordinates of the heating-surface.

The figure shows that if the heating-surface remains constant there will be an additional loss of heat for each additional increase of temperature. The only mode of preventing such loss is by extending the heating-surface. The proper rate of increase of heating-surface may be derived approximately from experiments.

The following results are taken from the published records of experiments made for the U. S. Navy under the direction of Mr. B. F. Isherwood. The first horizontal line represents the quantities of anthracite coal, in pounds, burned on each square foot of grate-surface in a marine tubular boiler, the heating-surface remaining constant and having a ratio of 25 to 1 to the grate-surface.

The second horizontal line represents the pounds of water evaporated under atmospheric pressure from 212° F. by one pound of coal.

Pounds of coal burned per hour.

6, 8, 10, 12, 14, 16, 18, 20, 22, 24.
10.5, 10.4, 10.1, 9.5, 8.9, 8.2, 7.7, 7.3, 7.0, 6.8.

Pounds of water evaporated.

A second series of experiments is furnished by Mr. D. K. Clark in his excellent work on Railway Machinery, in which he gives the amounts of evaporation for different *boilers* with varying rates of combustion, and varying proportions of heating-surface. The following results are extracted from his work. The first horizontal line of figures gives the quantities of coke burned per hour on each square foot of grate-surface. The second gives the quantities of heating-surface in square feet required to preserve the evaporation constant for each pound of coke, and equal to 9 pounds of water for each pound of coke burned.

Pounds of coke burned on each square foot of grate.

14, 19, 25, 31, 38, 47, 56, 65, 76, 87, 98, 110, 125, 139, 153.

30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100.

Heating-surface for each square foot of grate.

These two sets of experimental results serve to show how, in the first place, the economic evaporation varies with the rate of combustion, the heating-surface remaining the same; and in the second, how the heating-surface must vary if the rate of evaporation remains constant.

Inasmuch, however, as it is impossible to vary the heating-surface at will, after a steam generator is constructed, it is customary to fix the extent of this surface according to average conditions of use, taking into account average rates of combustion.

The following proportions represent as near as can be ascertained the usual rules of practice. The grate-surface being 1, the heating-surfaces are for

Plain cylinder boilers.....	10 to 15	average	12
Cornish boilers.....	30 to 40	"	35
French cylinder boilers.....	25 to 40	"	33
Cylinder flue boilers.....	17 to 25	"	21
Cylinder tubular boilers (chimney draft).....	25 to 30	"	28
Traction-engine boilers.....		"	32
Marine tubular and flue boilers—French, English, and American practice.....		"	25
Locomotive boilers.....	40 to 100	"	75

The rates of combustion per hour and per square foot of grate, in ordinary practice, are, according to Rankine,

Slowest rate in Cornish boilers..	4 lbs. per hr.
Ordinary rate.....	10 " "
Ordinary rate in factory boilers.	12 to 16 " "
Ordinary rate in marine boilers.	16 to 24 " "
Locomotive boilers.....	40 to 120 " "

A general rule is given by Morin and Tresca for the quantity of coal consumed per hour, viz.: that "boilers will have

favorable conditions of heating-surface, if the consumption of fuel per square foot of heating-surface does not surpass the quantities given below : ”

“ *Land boilers*, 0.6 pound of coal consumed for 1 square foot of heating surface.”

“ *For marine boilers*, 0.5 pound per square foot.”

“ *For locomotive boilers*, 0.8 pound per square foot.”

This corresponds to a proportion of heating-surface for land boilers (French boilers) of 24 to 1 ; for marine boilers, 28 to 1, and for locomotive boilers, 70 to 1 ; and to a rate of combustion per square foot of grate of 14.4 lbs., 14.0 lbs., and 56 lbs.

It is customary in England to estimate the heating-surface by the amount required to evaporate one cubic foot of water from 60 at 212°, and a cubic foot of water evaporated per hour is estimated to give a *nominal* horse-power. Armstrong’s rule, “ a yard of heating-surface to a horse-power,” for the old wagon boiler, is founded on this idea, since it requires about one square yard of heating-surface, and one square foot of fire-grate, to evaporate one cubic foot of water in these boilers. The propriety of this rule is, however, questionable, since it is not applicable to other forms of boilers, and the term horse-power, as applied to boilers, is improper, unless the pressure of the steam is taken into account, and even then it is to be estimated independently of the engine in which the steam is utilized, and is an arbitrary measure of capacity.

The quantity of heating-surface necessary to evaporate one cubic foot of water is however a proper basis of estimate of heating-surface, provided the type of boiler and the rate of combustion are given, and it is usual in such cases to state how many pounds of water will be evaporated by each pound of coal ; the amount of heating-surface is in this manner connected with the rate of combustion.

In a recent report of a committee of the Franklin Institute (Journal of the Franklin Institute, 1872), the mode of estimating heating-surfaces of Cornish boilers by Messrs. Easton and Anderson, of London, is given, from which it appears that the area of the under-side of the shell and the area of the top-half of the flues constitute the heating-surface ; and of this 12 square feet are allowed to evaporate one cubic foot of water per hour from 60, and at 212° F. The committee give also the heating-surfaces of various boilers re-

quired to evaporate one cubic foot of water per hour at 212° viz.:

Plain cylinder boilers (corresponding to the old wagon boiler).....	8.8	square feet.
Galloway multitubular boiler (water-tube boiler).....	8.5	"
Marine tubular boiler.....	14	"
Double-flue Cornish.....	11.7	"

For these the rate of combustion is such that the total heating-surfaces are sufficient to evaporate nine pounds of water for one pound of coal.

The following conclusions are deduced by the committee from Mr. Isherwood's experiments. The boilers of various steamships on which experiments were made, with the results, are indicated by the names of the vessels:

Jacob Bell.....	Marine tubular.....	19	12	11
Mt. Vernon.....	"	19	10.5	10.5
Valley City.....	"	16	11.2	9.16
Crusader.....	"	16.8	11.8	9.3
Wyandotte.....	Ver. water-tubes.....	20	12.4	10
Underwriter.....	Hor. flue boiler.....	15.6	11.2	9.9
Young America..	" "	15	10.4	9.3
Boston, of N. Y..	Marine tubular.....	18	11.1	11.5
				82.1
				10.2

1st column.—Heating-surface required per indicated H. P.

2d column.—Water evaporated per hour per pound of combustible.

3d column.—Combustible in pounds burned per hour per square foot of grate.

The practice of the Navy Department, according to the committee, is to allow 8 pounds of anthracite coal per hour to evaporate 1 cubic foot of water at 212°, under a pressure of 30 pounds per square inch, which requires $\frac{2}{3}$ square foot of grate and $16\frac{2}{3}$ square feet of heating-surface.

If the evaporative powers of different boilers be referred to the heating-surface, it will be found that the quantity evaporated for each square foot of heating-surface of the plain cylinder boiler appears greatly in excess of the quantity evaporated

by one square foot of heating-surface of the flue and tubular boilers. In the plain cylinder boiler the heating-surface is universally estimated by taking the lower half of the shell only, as this is the only part exposed to heat. But it would undoubtedly be more in accordance with the process of the transfer of heat to add to the heating-surface the bottom of the flue beyond the furnace that leads to the chimney, because this becomes intensely heated and must give off by *radiation* to the opposite surface nearly as much heat as the latter receives by the direct contact of the gases. So also with all internal as well as external fire-flues, the total internal surfaces should be considered as heating-surfaces, though not technically answering to the definition in all cases. If this principle be adopted, the heating-surface of the plain cylinder boiler, and of all external furnace boilers, will have the same value as other heating-surfaces, and the evaporation per square foot of heating-surface will correspond, nearly, for all boilers which have the same amount of heating-surfaces and rates of combustion, and the ratio of heating-surface to the grate-surface will approach uniformity for all boilers for the same rates of combustion.

For example, the rate of evaporation of plain cylinder, cylinder flue, and cylinder tubular boilers, per square foot of heating-surface, is in practice according to the present modes of estimating heating-surface :

Plain cylinder boilers.....	6.4	lbs.	of water	per hour.
Cylinder flue boilers.....	4.8	"	"	"
Cylinder tubular boilers..	4.3	"	"	"

If now we add for the plain cylinder boilers and return-flue and tubular boilers, to the heating-surface estimated in the usual way, the additional radiating surface of the bottom of the external flue, we shall have for each of these three external furnace boilers, a rate of evaporation per square foot of heating-surface approximately equal to 4.0 pounds of water per hour.

The *extent* of heating-surface is still practically less for the plain cylinder than for the others, and it is for this reason less efficient.

The quantity of water evaporated per pound of coal for each of these three boilers in the order given is, under the most favorable circumstances, 7, 8, and 9 pounds of water for each pound of coal burned, and these figures will represent, according to the

method proposed, the relations of the heating-surfaces in each for the same rates of combustion.

The railroad locomotive is the only boiler in which the rates of combustion are frequently and greatly varied while in use, and in these boilers it is necessary to provide for very high rates of combustion by giving an extreme amount of heating-surface.

The locomotive boiler, with ordinary rates of combustion, corresponds, in evaporative efficiency, to the ordinary marine tubular boiler.

The following results on the evaporative efficiencies of the sectional boilers are from the report of the committee appointed by the American Institute, to which reference has been made.

237. *Root Boiler*.—Grate surface, 27; ratio of heating-surface to grate, 32.5 to 1; coal burned per hour per square foot of grate, 11.73 pounds. Actual evaporation per pound of coal, 7.34 pounds of water; per pound of combustible, 8.76 pounds; equivalent evaporation at 212°, 10.64 pounds.

238. *Allen Boiler*.—Grate, 32½ square feet; ratio of heating-surface to grate-surface, 28.5; coal burned per hour per square foot of grate, 13.88 pounds. Actual evaporation at 75 pounds per pound of coal, 7.38 pounds of water; actual evaporation per pound of combustible, 8.76; equivalent evaporation at 212° F., 10.60 pounds of water.

239. *Phleger Boiler*.—Grate, 23 square feet; ratio of heating-surface to grate, 26.1 to 1; coal burned per square foot of grate-surface, 10.13 pounds; actual evaporation at 75 pounds pressure per pound of coal, 7.07; actual evaporation per pound of combustible, 8.70; equivalent evaporation at 212° F., 10.49 pounds of water. The amount of heating-surface necessary to evaporate 1 cubic foot of water per hour in these boilers was respectively 23.59, 17.41, and 22.74 square feet.

240. *Causes which affect the efficiency of evaporation*.—These are, 1st, those which influence the *rate of combustion*, and, 2d, those which influence the *rate of transfer of heat*.

Among the causes which influence the rate of combustion may be mentioned—

The temperature of the external air.

The temperature of the chimney gases.

The presence of moisture in the air.

The management of the fires, the quality of the fuel, and defective combustion.

The principal causes which affect the transfer of heat are—

The rate of combustion, which determines the initial temperatures in the boiler.

The temperature of the water in the boiler.

The accumulations of incrustations and dust in the tubes, and generally all those circumstances which impair the qualities of the heating-surfaces.

The influence of the external temperature and of the barometric pressure on the rate of combustion cannot well be estimated. An increased density of the external air favors combustion by increasing the draft, and also because a less volume of cooler air is necessary to burn one pound of combustible. The draft of chimneys is thus rendered more active in winter than in summer.

The influence of the internal temperature of the gases has less effect. It is pointed out by Peclèt that the maximum draft occurs only with an infinite degree of temperature in the chimney, but that a temperature of about 600° F. gives $\frac{7}{10}$ of the maximum.

The statement in Rankine that the maximum quantity of air drawn in occurs for a temperature of the heated gases of about 600° F. seems to be an error, as no such theoretical maximum exists in the formula for draft that has been given.

The influence of the moisture in the atmosphere is often important. In proportion as the moisture in the air augments, the fires languish, especially with a feeble pressure—a dry, cold air, with a high barometer, being more favorable to combustion. It is stated by Peclèt that in many of the glass factories of France work is suspended in summer on this account.

The management of the fires and the quality of coal is one of the most important influences on the rate of combustion and economy of fuel. It is stated by Morin and Tresca that the Industrial Society of Mulhouse offered a reward of five silver medals, and three sums of money, to the stokers who should show themselves, in a competitive trial, the most skilful in the management of the fires of a boiler. The results showed a difference of 13 per cent. in the extremes of the quantities of water evaporated under conditions precisely similar. If this difference could occur in a trial between stokers of acknowledged skill, what must be the effect of ignorance and carelessness combined?

241. Of the causes which affect the transfer of heat, and thus affect the rate of evaporation, the rate of combustion has an effect which gives rise to an increased rate for high rates of combustion with the same heating-surface. The same amount of heat is evolved whether the rate of combustion be slow or rapid; but to prevent loss additional heating-surface is required for high rates of combustion. It is necessary to distinguish between the rate of evaporation for a given heating-surface and the total heat evolved and transferred.

In order that no loss shall occur, it is necessary that the heated gases should always enter the chimney with the least practicable temperature.

The condition of the heating-surfaces is a matter of importance in connection with the rate of evaporation. Internal deposits of all kinds, whether from incrustation or from the accumulation of dirt, cause a loss of heat, as well as the destruction of the heating-surfaces; new boilers are, for these reasons, more efficient than old ones.

The effect of the pressure in the boiler is very slight. There is some loss in the rate of transfer as the pressure is increased, owing to the fact that the temperature of the absorbent is increased, and the rapidity of transfer depends on the difference between the temperatures of the source and the absorbent. It is impossible to estimate this loss, which is, however, only slight. As to the quantity of heat necessary to evaporate water at different temperatures, the total heat required increases slightly with the temperature, but the increase is insignificant; the difference between 1 and 6 atmospheres being only about .02 of the total amount.

242. In regard to the mode of estimating heating-surfaces, there has been a great deal of uncertainty, and great diversity of practice. A portion of the heating-surface is exposed to the direct radiation of the grate, and at the same time to the contact of the heated gases at their initial temperature; and some engineers, for this reason, divide the heating-surface into two parts, direct and indirect heating-surfaces. The direct heating-surfaces bear to the total heating-surfaces proportions which differ in the different types. In the locomotive, for instance, it is about $\frac{1}{4}$ of the whole; in marine boilers, about $\frac{1}{8}$; in cylinder-tubular and flue boilers from $\frac{1}{4}$ to $\frac{1}{2}$.

There is no doubt that the direct heating-surface is the most

efficient, since the quantity of heat transferred by direct radiation in a given time, from one square foot of surface, with a given difference of temperature, for the great differences which occur in boilers, is much more, probably 6 to 8 times more, than the quantity transferred by contact of the gases for the mean temperatures of the flues. But it is impossible to separate these influences, and it accords with the best practice to consider the heating-surface as a whole.

There seem to be stronger objections still to an arbitrary division of the surfaces of flues into parts of greater or less efficiency, when there is no possibility of ascertaining the value of those parts as regards efficiency, and especially as there appears to be actual misapprehension in regard to the action of these surfaces.

If the under-side of a flue is to be left out of consideration, the question may be asked, what becomes of the heat transferred to it; for there must be heat transferred to it by contact of the gases. There is no doubt that the overheating is prevented in part by radiation across the flue to the opposite side, and this radiation tends to equalize the temperature of the flue around its entire circumference. For similar reasons the outer surfaces of external flues should be taken into account. The contact of the heated gases would otherwise heat the sides of the external flues to a red-heat nearly, and such a heated surface near a flue, it must be acknowledged, would radiate heat rapidly across the space which separates it from the metallic plate of the boiler.

It seems, therefore, advisable to estimate *all surfaces* of flues, both of external and internal flues, as heating-surfaces. Some of the anomalies in regard to the efficiency of heating-surfaces would then disappear.

243. *Proportions of Water-room and Steam-room.*—The total internal volume of a steam generator may be divided into two parts, that which is ordinarily occupied by water and that which is occupied by steam.

It has been customary in England to fix the volume of steam-room at ten cubic feet for each cubic foot of water vaporized per hour. This proportion is based on the idea that a certain reserve of steam is desirable in proportion to the water evaporated per hour. The proportion seems unnecessarily great unless the steam-dome is included. Without the steam-dome a

proportion of five cubic feet for each cubic foot of water evaporated per hour accords more nearly with practice. According to Bourne, the water-room should be three-fourths and the steam-room one-fourth of the whole internal capacity. Armstrong recommends equal proportions of water-room and steam-room. The proportions should be in reality different for different boilers. For land boilers, three-fourths water-room and one-fourth steam-room may be regarded as a good proportion. For marine boilers, nearly equal proportions, and for locomotives about two-thirds water-room and one-third steam-room may be taken as average proportions.

244. *Priming.*—Priming consists in the carrying of particles of water, mechanically, into the delivery pipes of a boiler, and thence into the cylinder of the engine (where an engine receives the steam), and is caused principally by deficiency of the steam-room; or, at least, a deficiency of the free surface, or water-level. It is also caused by impurities in the water. The provision of a large steam-space, especially where there is a limited free surface, is therefore important, to prevent priming.

The effect of an over-full boiler in causing excessive priming is a matter of common observation.

245. *Proportions of the Furnace.*—The height of the crown of the furnace above the grate-bars is seldom less than eighteen inches, even in small boilers, and should always be greater than this if practicable. In locomotive boilers this height is generally about four feet. A high furnace is favorable for complete combustion. The height is limited practically, in boilers which have return-tubes or flues, by the necessity for having sufficient depth of water above the crown to cover them. In marine and land boilers ten to twelve inches' depth over the flues is advisable; in locomotive boilers, five to six inches.

246. *Actual Dimensions.*—In deciding upon the actual dimensions of a steam generator, required for a special purpose, the engineer is supposed to know the quantity of steam required per hour and the pressure at which it is to be produced.

The quantity may be given in cubic feet or in pounds, and the volume or weight required for any given pressure may be found from the table in this work which gives the specific volumes or specific weights, page 63. The weight of steam used per hour is always sensibly equal to the weight of water evaporated, and a boiler, or set of boilers, is to be chosen which will

evaporate the required quantity of water per hour. From what precedes, it may be assumed that the problem of actual dimensions is indeterminate without some other specifications than the quantity of steam required and the pressure, because there may be any number of boilers of different dimensions that will answer the purpose. To illustrate: let it be required to construct a tubular boiler that will evaporate 5,000 lbs. of water per hour, at any given pressure. If we suppose the boiler to be furnished with a steam jet, by which a rate of combustion of 60 lbs. of coal per hour for each square foot of grate may be attained, each lb. of coal will evaporate about 7 lbs. of water, if the heating-surface bears the proportion of 70 to 1 of grate; 12 feet of grate-surface and 840 of heating-surface will then be approximately the elements which will determine the actual dimensions. If the boiler, on the other hand, is to be attached to a chimney, with such a draft that only 12 lbs. of coal will be burned in an hour on each square foot of grate-surface, each pound of coal will evaporate about 9 lbs. of water, if the boiler be supplied with 25 square feet of heating-surface to 1 square foot of grate-surface. Under these conditions 48 square feet of grate-surface and 1150 feet of heating-surface will determine the dimensions approximately.

In the first case, $60 \times 12 \times 7 = 5040$, and in the second, $48 \times 12 \times 9 = 5184$ pounds of water will be evaporated. Any number of different combinations might thus be found, each of which would accomplish the same result. The considerations which influence a choice may be derived from an examination into these two cases in detail.

In the first case, 720 pounds of coal are required to evaporate 5040 pounds of water in an hour; and in the second, 576 pounds of coal; the difference, 144 pounds, being the amount of coal in favor of the slower combustion and larger grate-surface. The boiler of large capacity has the advantage, also, in steadiness of pressure, freedom from priming, and space for the collection of sediment; moreover, the durability of boilers is greater when the apparatus is subjected to less extremes of heat. The points in favor of the smaller capacity are, rapid raising of steam, small surface for waste heat, economy of space and of weight, and greater strength with a given quantity of material.

For a portable boiler the least weight is desirable, and a high rate of combustion, even with a sacrifice of economy of fuel,

may be preferred. On the other hand, if a chimney-draft is employed for the combustion, an excessive rate can only be attained by a very high chimney, which involves extraordinary expense.

These considerations are sufficient to show the various grounds of choice.

Generally these are sufficiently fixed by circumstances of use. For marine purposes, for instance, economy of fuel is of the greatest importance, especially as all the fuel for a voyage must be carried from the point of departure. Steadiness of pressure and supply of steam are also important. The chimney is in this case the ordinary means of draft (the exhaust-steam being usually condensed), and it is necessary to keep the chimney as low as possible. All these considerations tend to fix the conditions for marine boilers, and hence the rule given in a preceding paragraph as to the practice of the U. S. Navy Department for heating-surface and grate-surface. In railroad locomotives, on the other hand, the least weight practicable is desired, and the loss of economic effect in fuel is more than counterbalanced by the saving effected by the lesser load to be transported. For land boilers, with chimney-draft, the heights of chimneys are such as to cause a combustion of 12 to 18 pounds of coal per hour on each square foot of grate. *Here there is occasion for discrimination*, and the amount of grate-surface should be first determined from the *probable* rate of combustion, and the total quantity of combustible required per hour to evaporate the required quantity of water. The grate-surface having been thus estimated, the other dimensions will follow from the proper proportions applicable.

It is hardly necessary to state, after what precedes, that the inverse problem is equally dependent on the conditions which have been enumerated.

For example, having a given boiler, to ascertain what quantity of water can be evaporated by it in an hour, it is necessary to know the quantity of coal burned per hour, or rate of combustion, for each square foot of grate-surface, and also the quantity of heating-surface, in order that the quantity of water evaporated by each pound of coal per hour may be determined.

247. *Efficiency of Steam Generators.*—By efficiency is to be understood the quantity of heat transferred to the water, in proportion to the total quantity evolved by the combustion.

The total heat of combustion of one pound of coal is sufficient to evaporate about 15 pounds of water, the water being supplied and evaporated at 212° Fahr.

The ordinary evaporation is, as has been shown, from 7 to 9 pounds in current practice. The efficiency will be $\frac{7}{15}$ to $\frac{9}{15}$. The differences between 7 and 15 or 9 and 15 (round numbers being given), will represent in each case the waste heat and the heat required to produce the draft, where there is a simple chimney draft; in other cases the waste heat alone.

The waste heat arises from several causes :

1. Waste of unburnt fuel in the solid state.
2. Waste of unburnt fuel in the gaseous or smoky state.
3. Waste by external radiation and conduction.
4. Waste by the excess of heat which escapes by the chimney, over that required for the draft.

These sources of waste may give rise to excessive losses which perfect arrangements and good management are intended to avoid. If the arrangements and proportions adopted by the engineer are suitable, the stoker is generally responsible for a large part of the waste which may occur in the combustion.

An excessive quantity of coal in small unburnt, or partially burnt, pieces in the ash-pit, is evidence of direct carelessness or inattention. Irregular and excessive charges, especially when attended by irregular cleaning of the grate, are very sure to cause waste, through the chimney, of combustible gases and smoke. The waste by radiation and conduction is to be prevented as much as possible by proper non-conducting and non-radiating materials, such as felting for the covering of the shell, or brick chambers enclosing the boiler. Waste by excessive heat in the chimney ought not to occur when there is sufficient heating-surface, and when the heating-surfaces are kept in good condition.

The accumulation of internal deposits and incrustations, however, often causes a steady diminution of efficiency in boilers which are constantly in use; a diminution which cannot be prevented.

In furnaces in which the draft is produced by a blast, or fan, all the heat which passes through the chimney must be considered as waste.

In regard to the amount of these different elements of waste, it may be said that the loss from the occurrence of unburnt

combustible in the ash-pit may be in some degree prevented by a careful sifting or raking of the ashes. Some ashes contain large quantities of coke, besides small pieces of unburnt coal, which can be saved.

The waste by the escape of combustible gas (carbonic oxide) may amount to one-tenth of the whole heat.

The amount of heat lost by the high temperature of the escaping gases depends not only on the temperature of the escaping gases, but also on the quantity of air admitted for each pound of coal burned. Where an excessive quantity of air is admitted, and a high temperature prevails in the chimney, the loss may be very great. The most favorable conditions are when the quantity of air admitted is just sufficient for combustion, and the heat of the chimney just sufficient to produce the draft.

The most unfavorable circumstances which can ordinarily occur are those in which the quantity of air admitted is about three times the theoretical quantity (the initial temperature of the gases consequently low), and when the temperature of the chimney gases is high.

It is impossible to estimate the loss of heat by radiation and conduction through the masonry, by the entrance of air through joints into the tubes and chimney, and by radiation from the shell; but it is certain that these causes of loss are such that it is important to prevent, by the most efficacious means practicable, all access of air, except at the points where it is needed for combustion, and to guard against loss by conduction and radiation by proper non-conducting materials and arrangements for the furnace, the flues, and for the shell.

The efficiencies stated above are by no means the highest that ought to be attained, nor are they the lowest that probably occur in most manufacturing establishments. There is no doubt that a saving of 20 per cent. and often 30 per cent. of the quantities of coal now consumed in many manufacturing establishments might be effected by the introduction of more perfect proportions and arrangements, and especially by the employment of *thoroughly skilled and intelligent stokers*. There is greater prospect and room for improvements in these respects than through any new inventions or devices for boilers.

248. *Horse-power of Boilers*.—The term *horse-power* can hardly be applied with propriety to steam generators, inasmuch

as it implies a rate of work, and a boiler ordinarily does no work, but merely supplies the means of work to a machine. The amount or rate of work is thus dependent on the utilization of the steam, and must vary with the variations of the machine which utilizes it. Moreover, the application of this term to boilers is especially inappropriate when it is determined solely by the dimensions of the boiler, as is usually the case; a boiler of certain dimensions being spoken of as a boiler of 10-horse power, another of larger dimensions as one of 20-horse power, etc. In reality, a boiler called a 10-horse-power boiler may, according to any rational rule which can be adopted, be made a 20-horse-power boiler by simply increasing the rate of combustion, or the pressure of the steam, or both combined. A railroad-locomotive boiler, for example, in the course of a single trip may vary extremely in these particulars, and will at one time produce steam in large quantities under high degrees of pressure, and at another greatly reduced quantities of steam under reduced pressures; and yet, according to the current ideas of horse-power of boilers, it would all the time be a boiler of a fixed horse-power.

This becomes a matter of some importance when boilers are bought and sold according to their *horse-power*, because in case of dispute it is impossible to attach definite ideas to the terms employed, unless it be at the same time specified what is to be the rate of combustion, and the pressure. The rate of combustion is subject to such variable conditions that it is difficult to establish it precisely, and the custom of describing the capacity of boilers by the term horse-power is, therefore, liable to lead to difficulty.

It may be desirable, however, to have a standard for the capacity of boilers in order to compare the work actually accomplished, under different circumstances by the steam furnished, with this standard. The maximum quantity of work which the steam from a boiler is capable of exerting, for a given rate of evaporation and a given pressure, in a perfect engine, may easily be found; a *perfect* engine in this respect being one in which there is no clearance, and in which the pressure of the steam is the same as that in the boiler, the counter-pressure being the pressure of the atmosphere or of the condenser, and the pressure diminishing by the expansion from that of the boiler to that of the atmosphere or condenser; and

finally, no resistance being offered to the flow of steam through the pipes and valves. Such an engine cannot be constructed, but is theoretically supposable.

The quantities of water or steam, in pounds, required to produce one horse-power per hour for non-condensing and condensing engines under these circumstances, for different pressures, is as follows (the figures being taken from Professor Zeuner's work on the mechanical theory of heat, English measures being substituted) :

Tension of Vapor in Atmospheres.	Pounds of Water per Horse-Power per Hour.	
	Non-condensing Engine.	Condensing Engine.
1½	72.9	15.6
3	32.8	12.7
4	26.3	11.8
5	22.9	11.3
6	20.7	10.8
8	18.0	10.3
10	16.5	9.9

If we take as the standard the *perfect non-condensing engine*, the available capacity of the steam for any boiler may be found in *horse-power* by dividing the number of pounds of water evaporated per hour, at a given pressure, by the number of this table for the same pressure in the second column. Another method may be derived from calculations based upon the *living force* of steam issuing from an orifice in a boiler into the atmosphere.

The velocity of efflux being independent of the area of the orifice, we may also suppose it to be uninfluenced by friction or other resistances. Under these circumstances the theoretical velocity may be found for different internal pressures, and a constant external atmospheric pressure. It is evident that when the size of the orifice is such that the whole work of the boiler consists in forcing into the atmosphere the steam generated, if

w be the weight of steam generated in a minute, the work per minute will be equivalent to $\frac{w v^2}{2 g}$, and the number of *horse-power* $\frac{w v^2}{2 g \ 33,000}$.

The following theoretical velocities are taken from Professor Zeuner's work :

Pressures in the Boiler. Atmospheres.	Velocities in Metres per Second.
2.....	481.71
3.....	606.57
4.....	681.48
5.....	734.32
6.....	774.89
7.....	807.57
8.....	834.90
9.....	858.33
10.....	878.74

For these velocities the values of $\frac{w v^2}{2 g \ 33,000}$, found for the same pressures respectively, are :

Pressures in Atmospheres.	
2.....	$1.11 \times w = \text{number of horse-power.}$
3.....	1.87 “
4.....	2.34 “
5.....	2.75 “
6.....	3.07 “
7.....	3.35 “
8.....	3.58 “
9.....	3.80 “
10.....	3.95 “

The numbers of this table multiplied by the quantity of water, in pounds, evaporated *per minute* will give the horse-power of the boiler, when it performs the work of forcing steam into the atmosphere under the conditions stated.

These two methods, though accomplished by different pro-

cesses, should give identical results. It was pointed out by Professor Zeuner that the living force of steam issuing from a boiler, under the circumstances mentioned, is equivalent to the work performed by the steam in a perfect engine, equal quantities being considered.

The actual work of ordinary steam-engines falls, of course, much below the theoretical, the efficiency depending upon the approximation to the perfect conditions already named.

The quantities of water actually required in practice for one horse-power per hour, in small non-condensing engines working under the most favorable degrees of expansion practicable, are approximately as given below :

TABLE XXX.

Experimental and Theoretical Quantities of Water required in Non-condensing Engines for one Horse-power per Hour.

Results of Experiments on small Engines by Mr. C. E. Emery.		Theoretical Quantities.
Pressure of Steam in Pounds.	Water required per Horse-power per Hour in Pounds.	Water required per Horse- power per Hour in Pounds.
30	56	58
35	51	45
40	48	37
45	45	32.5
50	43	29.5
55	41	27.5
60	39	26
70	37	23
80	34	21.5
90	32	20.3
100	31	19.5

The above results of experiments are probably near the highest limits of economy attainable for the different pressures given, and the numbers in the second column represent the

lowest quantities of water ordinarily reached in practice with small engines for the production of one horse-power per hour. The theoretical results in the third column are for a theoretically perfect non-condensing engine.

Suppose now a boiler to evaporate, at 100 lbs. pressure, 3,000 pounds of water per hour, the horse-power of the boiler will be, according to table, $\frac{3,000}{60} \times 3.27 = 163.5$ H. P.

The actual performance of a small engine will give, according to the experimental results in the last table, $\frac{3,000}{31} = 96.8$ H. P.; about 59 per cent. of the theoretical rate of work in a perfect engine, or of the rate of work performed by a boiler in forcing steam through an orifice, without friction, into the atmosphere.

In regard to the use of the term *horse-power*, it must be admitted, however, that it is a convenient mode of designating the capacity of land boilers, where average conditions of pressure and rate of evaporation are understood.

There is, however, a want of uniformity among manufacturers in regard to what amount of heating-surface shall constitute a horse-power, with chimney-drafts; the amounts varying from 12 to 18 square feet.

249. *Kind and Quality of Materials.*—The materials employed in the construction of boilers consist of plates, rolled or shaped into the forms necessary for the shell, tube-sheets and flues; tubes, or flues, formed by drawing, or by lap-welding; rivets for the joints; rods acting as stays; plates, or castings, for the fronts and doors, and bars for the grates. Where boilers are set in brick-work it is to be understood that the external work is to be of a character such as will resist the action of heat as well as prevent its dissipation through radiation and conduction.

The materials now universally used for the shell are wrought iron and steel. Cast iron is sometimes employed for the heads of small cylinder boilers, and for steam-domes or steam-chambers, but owing to its rapid deterioration under the action of heat it is not a suitable material for heating-surfaces. It is, however, employed largely in the fronts, grate-bars, for attachments for valves and pipes, and for man-hole and hand-hole plates.

Copper was formerly used for the shells of marine boilers to

some extent before a full knowledge was acquired of the favorable properties of wrought-iron plates for being worked into angular shapes by bending and hammering (technically called "flanging"). This material is now confined, however, in use, to the fire-boxes of locomotives, and in some cases, as in fire-engine boilers, to small tubes.

Iron boiler-plates are found in the market, in this country, under three general designations, which indicate to some extent not only the qualities of the plates, but also the modes or processes of manufacture.

Plate-iron called C. No. 1 (charcoal No. 1; or iron manufactured by employing charcoal as fuel in the blast-furnace), should be used only in parts of boilers which are not subjected to high degrees of heat. Although the best varieties possess sufficient strength for the shells of boilers, it is unsafe to use this quality of iron in the furnaces.

Iron called C. H. No. 1 (*charcoal-hammered* No. 1), and also "flange iron," comprises plates in which the "piles" are reheated and *hammered* with heavy steam-hammers. This process gives greater compactness and solidity to the plate, and improves not only its strength, but also its capacity for resisting high degrees of heat.

Fire-box iron designates a kind of plate-iron made exclusively for furnaces.

Of each of these kinds there are many different qualities, depending on the details of the processes in the different factories, and the care with which the iron is selected and the plates fabricated. In this branch of manufacture, as in others, the standing and reputation of particular manufacturers is derived from long-continued and satisfactory use of their products, and is a sort of guarantee of quality.

For manufacturing C. No. 1 boiler-plate the iron used is generally cold-blast charcoal-iron. The pig-metal is remelted and refined, or converted into wrought iron, in charcoal fires, the balls being hammered into blooms. These blooms are reheated in reverberatory furnaces, and then rolled into slabs about one inch thick. These pieces are called covers. Between two covers clippings of boiler-plates are compactly placed, and the "pile" is then reheated to a welding heat, and passed between heavy rolls. Common wrought scrap is sometimes piled between the covers, and of course the risk of obtaining inferior iron is

thus increased, owing to imperfect welding of the pieces, from the occurrence of slag between the layers.

Iron manufactured by this process of covers and filling is liable to blister under intense heat, on account of its laminated character, and from imperfect welding.

The charcoal-hammered iron is that which is produced by piling one slab or bloom upon another, no scrap being introduced between the blooms, or by piling compactly bars at right angles to each other; the piles being then rolled under a high welding heat to compact the mass, and generally reheated and hammered or rolled several times. The quality known as C. H. No. 1 should not be formed of covers and scrap, whether the piles be hammered or rolled; but should be made of a compact mass of homogeneous material solidly welded under high welding heats. This process is employed to produce *fire-box* iron also, which differs from the C. H. No. 1 generally in being subjected to one or two additional processes of heating and hammering or rolling; and in which the greatest care is observed in the selection of the material.

It is easy to see how much depends in the quality of iron boiler-plates on the manufacturer, and that there may be as great differences in quality in this article of commerce as in fabrics of cotton or wool. It is difficult to detect on a superficial examination differences in quality, as the surfaces of different qualities appear the same. As a general rule, plate-iron which can be bent to right angles when heated to a red-heat without showing cracks may be relied on for all parts of boilers; and the indications are still more favorable if such a test can be successfully made when the plate is cold. None but the very finest qualities will bear this latter test.

The superiority of steel plates is exhibited under these tests.

Where a test by actual bending or working is impracticable, the hammer test may be applied. Each plate is "sounded" with a light hammer by slightly tapping it at as many points as possible. Defects arising from imperfect welding or internal flaws will often be thus discovered. The best test for the tensile strength is the testing-machine; and where a large number of iron plates of one kind is to be used, it may be advisable to send samples to a testing-machine.

Steel plates are usually made from puddled or cast steel. The process of making puddled steel is to stop the ordinary

puddling process, by which wrought iron is made from pig iron, at the moment when the decarbonization is at the point required for steel.

Homogeneous steel is a cast steel produced by melting wrought iron of the finest quality in crucibles with carbonaceous matter: the ingots cast are heated and rolled into plates.

It is apparent that these steel plates must produce plates of superior quality, not only on account of their great strength, but also from their homogeneous character.

The disadvantages in the use of copper arise from its comparative weakness, especially under high degrees of heat, and its cost. For fire-boxes of locomotives it is almost exclusively employed in England, though the results of experience in this country seem to be in favor of iron for this purpose. Steel plates are used to a considerable extent for locomotive boilers, the advantages consisting in greater strength with the same weight, or equal strength with less weight; while this material, from its homogeneous, compact structure, resists, better than iron, some of the causes of deterioration, such as corrosion and attrition.

250. *Stays* are usually made of the finest quality of wrought iron, capable of bearing a tensile strain of 60,000 to 70,000 lbs. per square inch. Copper stay-bolts are commonly used for the fire-boxes of locomotives in England, and tubular stays are highly recommended by some engineers.

The material employed for rivets is usually wrought iron, the material being selected and the rivet-rods manufactured for this special purpose, so as to combine softness under the hammer with great strength.

Angle-iron is employed by English manufacturers for connecting the heads of boilers with the shells, and for uniting the ends of large flues to the heads; though its use for that purpose has not extended to this country. This is in part owing to the superiority of the best American boiler-plates for flanging.

Grate-bars are usually made in this country of cast iron. In England wrought-iron bars are used in locomotive boilers. The rapid deterioration of grate-bars renders their frequent renewal necessary, and as this is easily and readily accomplished, the choice of the least expensive material seems to be desirable. For boiler fronts and doors, man-hole and hand-hole plates, etc.,

a combination of cast and wrought iron is used. See Plates XXXV., XXXVI., XXXVII., pages 186*, 186†, 186‡.

251. *Strength of the Materials used in Boilers.*—Mr. C. B. Richards, engineer of the Colt's Arms Co., has recently made tests of several varieties of boiler-plates with the very accurate testing-machine of that company.

The tables and explanations are here introduced without comment, as Mr. Richards's skill and accuracy in experimental investigations of this kind are well known. The tables give a good idea of the resistance to tensile strains of the ordinary market varieties of boiler-plates.

The experiments of Robert Napier & Sons, on the strength of steel and iron boiler-plates, showed the mean resistance to tension of English wrought-iron plates to be 49,000 lbs. per square inch; the result of 150 experiments. The result of 80 experiments gave an average of 85,000 lbs. for steel plates. The greatest difference between the highest and lowest strengths of the *same brand* of iron plates was about 20,000 lbs. per square inch. For steel the greatest difference was about the same. The greatest *average* difference of strength of plates across and with the grain, was for iron 7,000 lbs., for puddled steel about 22,000 lbs., and for "*homogeneous*" steel 790 lbs. per square inch.

Fairbairn gives the average resistance of boiler-plates 52,000 lbs. per square inch.

TABLES

OF THE RESULTS OF A NUMBER OF EXPERIMENTS MADE

BY C. B. RICHARDS, ENGINEER,

ON THE

TENSILE STRENGTH OF BOILER-PLATES.

(Principally on those rolled by the Bay State Iron Company.)

TABLE I.

No. of Specimens broken.	KIND OF IRON.	Nominal Shape of the Specimens.	Direction of the Lamination, i. e. L. is Lengthwise, and C. is Crosswise.	Resistance to Tensile Strain per Square Inch of Original Cross-Section.				Approximate Dimensions of the Original Cross-Section.	Resistance per Sq. Inch of Fractured Area.
				Strongest Specimen.	Weakest Specimen.	Averages.	Averages.		
2	(From an old Boiler.) Thornycroft, English.....	Short	L	Lbs. 47245	Lbs. 46410	Lbs. 46827	Lbs. 45293	In. 0.87	Lbs.
2	Do.	"	C	44355	43165	43760	x 45293	x 0.27	
3	Pennsylvania "Common"	"	L	54699	44581	49227	x 48434	x 0.87	
3	Do.	"	C	54031	43476	47641	x 48434	x 0.16	
1	Pennsylvania "C. No. 1"	"	L	48660	53395	54306	x 51483	x 0.87	
2	Do.	"	C	55218	53395	54306	x 51483	x 0.28	
1	Pennsylvania "Flange"	"	L	54466	54819	51184	x 53733	x 0.87	
2	Do.	"	C	58450	51992	54264	x 53096	x 0.28	
4	Bay State "C. No. 1"....	"	L	53145	50449	51928	x 54925	x 0.28	
4	Do.	"	C	57934	54577	56165	x 54925	x 0.28	
2	Bay State "Flange"	"	L	53998	53995	53696	x 52750	x 0.28	
2	Do.	"	C	53751	52546	53168	x 52750	x 0.28	
2	Sligo "Fire-Box"	"	L	54394	50272	52333	x 52750	x 0.28	
2	Do.	"	C				x 52750	x 0.28	
1	(Specimen from a different source.) Do.	"	L			60911	x 1.265 x 0.329	x 1.265 x 0.329	

TABLE II.

14	Bay State "Flange"	Long	L	51378	44036	48098	x 47187	x 1.25	63596
12	Do.	"	C	49023	39898	46277	x 47187	x 1.25	52349
4	Bay State "C. No. 1"	"	L	48819	46086	47725	x 46013	x 0.30	55967
4	Do.	"	C	45240	42961	44301	x 46013	x 0.30	48849
4	Bay State Homogeneous Metal	"		71139	70100	70672	x 1.25 x 0.30	x 1.25 x 0.30	136473

TABLE III.

6	Bay State "Flange"	Long	L	47785	46484	47017	x 47450	1.25 x 0.29	64411
3	Do.	"	C	49113	46815	47884	x 47450	0.75 x 0.29	56755
6	Do.	Short	L	52993	50770	51943	x 52102	1.25 x 0.29	61295
3	Do.	"	C	53161	51597	52262	x 52102	0.75 x 0.29	58170

"The results given in these tables are from experiments with specimens of three different shapes, as below:"



"In all the experiments recorded in *Table I.* the specimens were shaped like either S or S', but as there was hardly an appreciable difference in the results from these two forms, they are not separated in the tables, and are styled 'Short' specimens."

"All the specimens from which *Table II.* is made up were shaped like L, and are called 'Long.'"

"The experiments of which *Table III.* gives a synopsis were made for the purpose of determining the influence of the shape of the specimen on the results obtained for the particular material then under test. All these specimens were taken from the same piece of boiler-plate, and the alternate pieces were cut into the form S and L respectively."

"*The breaking-strain per square inch of the area at the point of fracture, measured after fracture,* is given in Tables II. and III. That this value gives important information of certain qualities of the material in question, is indicated by the fact that it shows the difference between the toughness or ductility of the material when taken crosswise and lengthwise of the plate, better than the other values of breaking-strain do. The correctness of Kirkaldy's opinion on this point, founded on his experiments, has thus received additional confirmation."

"The want of agreement between the results given in Tables I. and II. for Bay State plate, is to be accounted for entirely by the difference in shape of the specimens; as shown by *Table III.*"

The tensile resistance of copper plates is about 36,000 lbs. per square inch.

The influence of heat upon wrought iron is to increase its tensile strength until a red-heat is *approached*, when its strength rapidly decreases. For copper, the decrease of strength commences at ordinary temperatures, and at about 1000° F. it loses its tenacity in a great degree.

252. *Theory of Stress in Boilers.*—By the term “stress” in applied mechanics is meant the force which acts directly upon the particles of any material to separate them.

In boiler construction the adoption of the cylindrical form for the shell and flues, or tubes, causes this stress to be always a tensile stress on the shell, on flues subjected to internal pressure, and on the stays. The stress is a compressive one on flues or tubes subjected to external pressure, and a shearing stress on rivets. Bending moments are carefully avoided in all parts of the structure.

The tensile stress upon the material of a cylindrical shell tending to rupture it longitudinally is found as follows: Let p denote the elastic force of the steam in pounds per square inch, d the diameter of the cylinder, t the thickness of the shell. If we consider unity of length of the cylinder, the total force tending to produce rupture will be $p d$, d being expressed in inches. The total resistance of the material will be $2 t \times f$, f being the resistance to tension of the material; and the conditions of equilibrium require that

$$p d = 2 t f,$$

from which the thickness of the shell is obtained—

$$t = \frac{p d}{2 f}$$

For the same internal pressure and the same material, the thickness for different diameters will be proportional to the diameter. For the stress in the direction of the axis of the cylinder, the total pressure in this direction will be $p \times \frac{1}{4} \pi d^2$, and the resistance of the material in the cross-section will be $f \times \pi d t$. Placing these quantities equal to each other, we have—

$$p \times \frac{1}{4} \pi d^2 = f \pi d t;$$

$$\text{or,} \quad p \frac{1}{4} d = f t$$

$$t = \frac{p}{4} \frac{d}{f}$$

This result shows that the area of resistance to rupture in the direction of the axis, *relatively to the total area of pressure*, is double that in the first case; or, in other words, the stress *per square inch* of material in the direction of the axis is only half that which tends to rupture the boiler along a longitudinal plane through the axis. The tenacity f may be taken for the *bursting tension*, the *proof tension*, or the *working tension*. Mr. Fairbairn gives the values of f for wrought iron: bursting tension, 34,000, proof tension, 17,000, working tension, 4,250 lbs. per square inch. This is equivalent to making the factor of safety 8, which, however, is greater than that usually adopted in practice. It is assumed that the working pressure, multiplied by the factor of safety, will produce rupture. If the working pressure be 60 lbs. per square inch, for example, a pressure of 480 lbs. per square inch will produce rupture. Ordinary boilers constructed for a working pressure of 60 lbs. will hardly bear, before rupture, 480 lbs. Proof-tests of double the working pressure are allowed, although these tests are generally limited to one and a half times the working pressure. Rankine states that the rule followed in England is to make the working pressure one-sixth of the bursting pressure.

253. *Joints*.—In the construction of boilers the junction of the plates requires special care and attention, inasmuch as the resistance of the joints determines the total resistance. Riveted joints are made in several different modes, the principal of which are the *lap-joint single-riveted*, the *lap-joint double-riveted*, the *butt-joint single-riveted*, and the *butt-joint double-riveted*. The stress upon the rivets is a shearing stress. The butt-joint is formed by adjusting the edges of two plates and covering the joint on both sides by covering-plates, riveted either with one or two rows of rivets on each side of the joint.

The construction of joints by these various methods is made on the following principles:

Let f denote the resistance per square inch of the material of the plate to tearing, f' the resistance of the rivets per square inch to shearing, s the sectional area of the plate which must be torn apart, s' the sectional area of rivets which must be sheared to produce rupture. Then there should exist the proportion $f s = f' s'$ or $\frac{s'}{s} = \frac{f}{f'}$. For wrought iron the resist-

ances to tearing and shearing are nearly the same, and $\frac{f}{f'} = 1$, and therefore s' should be equal to s . If t be the thickness of the plate, d the diameter of the rivets, c the distance from centre to centre of rivets, we should have for *lap-joint single riveted*, $\frac{s'}{s} = 1 = \text{sectional area of one rivet, divided by sectional area of plate between two rivet-holes.}$

$$= \frac{.7854 d^2}{t(c-d)}$$

from which

$$c = \frac{0.7854 d^2}{t} + d$$

d in practice is usually from $2t$ to $1\frac{1}{2}t$, and the overlap from c to $1\frac{1}{10}c$.

For overlapped double-riveted joints, by the same process the value of c may be found to be

$$c = \frac{1.5708 d^2}{t} + d$$

the overlap in practice being from $1\frac{2}{3}c$ to $1\frac{3}{4}c$.

For butt-joints with a pair of covering-plates, single-riveted, the value of c is the same as for overlapped double-riveted joints; the length of each covering-plate $2c$, the overlap = $2c$ to $2\frac{1}{2}c$. For double-riveted butt-joints

$$c = \frac{3.1416 d^2}{t} + d$$

the length of each covering-plate being $3\frac{1}{3}c$ to $3\frac{1}{2}c$.

The order of strength of these joints, in terms of the strength of the original plate, according to Clark, are for plates $\frac{3}{8}$ -inch thick and less,

		Working Strength.	
† Original strength of plate...	100	11,000 lbs. per sq. inch.	
Single-riveted lap-joint.....	60	6,700	" "
Double-riveted lap-joint.....	72	8,000	" "
Double-riveted butt-joint.....	80	9,000	" "

The above figures are given for the best English Yorkshire plates.

* Rankine.

† Holley.

Fairbairn estimates the strength of joints to be, in terms of the strength of the plate,

Strength of plate.....	100	Bursting tension.	34,000 lbs.
Double-riveted joint....	70	Proof tension....	17,000 "
Single-riveted joint.....	56	Working tension.	4,250 "

the working tension being $\frac{1}{8}$ of the bursting tension. For cast-iron pipes the working tension may be estimated at $\frac{1}{6}$ the bursting tension, and the values of the tenacity in practice may be estimated at

16,500 lbs. per sq. inch	for bursting tension.
5,500 " " " "	proof tension.
2,750 " " " "	working tension.

Welded joints for boilers have been found to possess the same strength as the original plate, but practical difficulties prevent the adoption of this process for ordinary work.

The thickness of boiler-plates is practically limited in both directions. Very thin plates cannot be caulked, and very thick plates cannot be riveted. The limits are practically about $\frac{1}{4}$ of an inch for the lower limit and $\frac{3}{4}$ of an inch for the higher limit. The riveting machine is essential for very thick plates, a thickness of half an inch being near the limit of hand-riveting. The usual thicknesses for boilers are $\frac{1}{4}$, $\frac{5}{16}$, $\frac{3}{8}$, $\frac{7}{16}$, $\frac{1}{2}$.

254. *Resistance of Flues to Collapse.*—The resistance of flues to collapse from external fluid pressure was found experimentally by Fairbairn to be inversely as the length, inversely as the diameter, and directly as a power of the thickness, which for practical purposes may be represented by 2; and the following formula is given by Rankine for the collapsing pressure of an iron flue. Let p be the collapsing pressure in pounds per square inch, t the thickness expressed in inches, d the diameter, also expressed in inches, and l the length expressed in feet. Then—

$$p = 806,000 \frac{t^2}{ld}$$

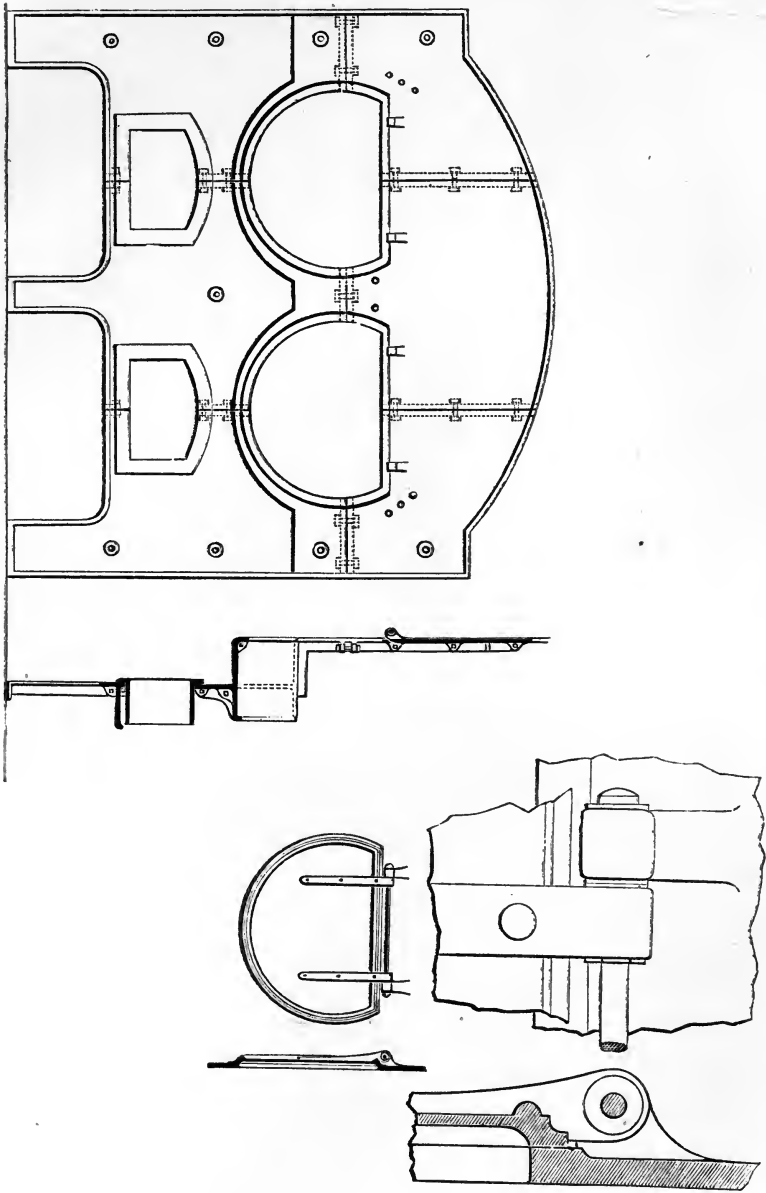
This formula is only applicable, however, for flues of ordinary lengths, such as those in use in steam-boilers. When flues are strengthened by angle-iron rings riveted around them the length l is to be taken between the rings. The plates from which large flues are formed are usually of the same thickness

with those of the shell. The resistance to collapsing between two rings should be equal to the resistance of the shell to the bursting pressure.

255. *Stays*.—Wherever flat surfaces occur, which are exposed to pressure, it becomes necessary to introduce stays or bolts to resist the pressure—the stays being connections between plates in the form of tie-bars, which resist the separation of the plates. Fig. 4, page 137, exhibits the mode of introducing stays for marine boilers, and Plate XXIV., page 138, the general method for locomotive boilers. Each stay sustains the pressure of the steam against a certain area of the plate to which it is attached, and the sectional area of the stay, multiplied by the resistance of the material per square inch, should be equal to the product of the area which is to be sustained, multiplied by the pressure of the steam per square inch. The factor of safety for stays is 8. The usual distance apart of the stays of locomotive boilers is $4\frac{1}{2}$ to 5 inches, and of low-pressure marine boilers 10 to 12 inches. Where the stays are likely to become corroded the working tension should not be greater than 3,000 to 4,000 lbs. per square inch, or, in other words, a larger factor of safety should be employed. The crowns of locomotive furnaces are usually hung by stays or bolts from a system of ribs or beams which cross it in parallel lines, the ends being supported on the front and back vertical ends of the fire-box, the beams being also hung from the roof or shell. The crown-sheets of the locomotive fire-boxes being usually flat, and being exposed to intense heat, the utmost care is necessary in this part of the construction. The pressure of 1 pound per square inch of steam, upon one square foot of surface, being equivalent to about the weight of one cubic foot of ordinary sandstone, and 100 pounds per square inch, consequently, will give a pressure equivalent, approximately, to the weight of a column of sandstone 100 feet high. The weight to be borne by the flat crown of a fire-box 3×4 sustaining a pressure of 100 pounds per square inch would thus be approximately equivalent to the weight of a column of sandstone having a base of 12 square feet and an altitude of 100 feet. It is this weight that must be resisted by the stays and their attachments.

The construction of cast-iron *boiler fronts*, for the setting of boilers in brick-work, is shown in Plate XXXV., page 186*. Plate XXXVI., page 186†, shows the ordinary construction of

PLATE XXXV.—Furnace Front. Cast Iron.





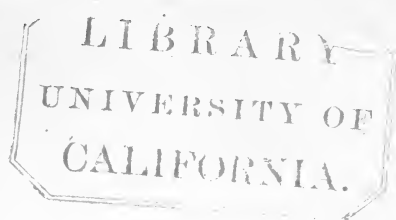
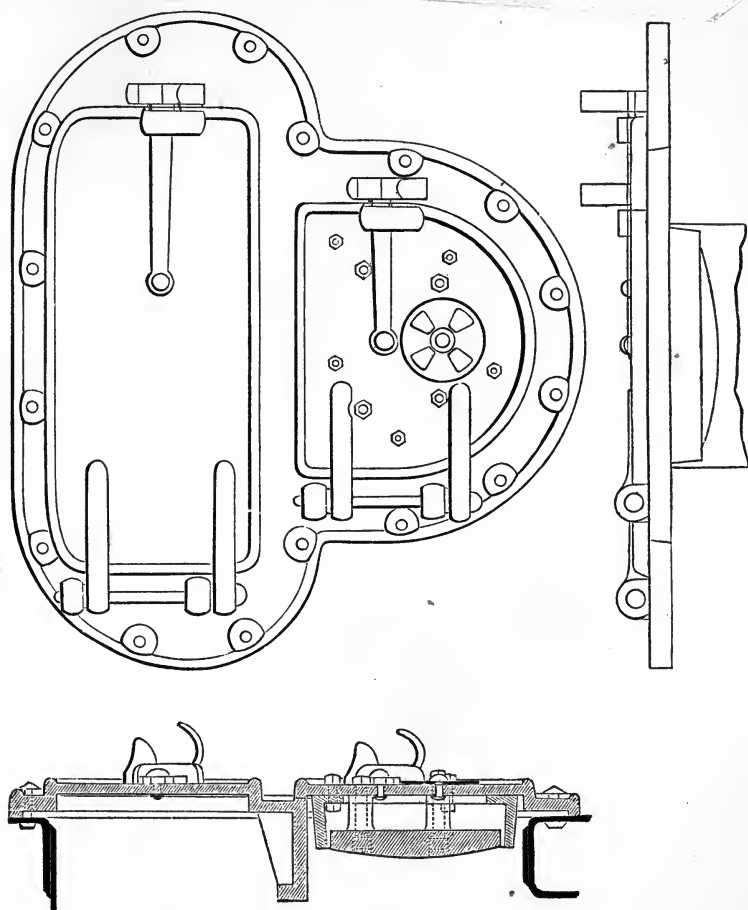


PLATE XXXVI.—Furnace door for Marine Boiler.





furnace doors for marine boilers, and Fig. 6, page 137, the usual method of setting grate-bars in marine boilers.

256. *Supply of Feed-water.*—The supply of water to a boiler is of course indispensable to its performance. It is usually accomplished by an independent apparatus, a pump or an injector being employed.

The capacity of the feeding apparatus should be such as to supply sufficient water not only for the highest rate of evaporation likely to be attained, but to supply all losses from priming, leakage, blowing off, etc.

Care should be taken that the feed-water does not impinge on the plates or flues, as the sudden cooling at one point is liable to fracture the plates. Such fractures cannot always be discovered when the boilers are inspected, and are always a source of danger.

For land engines a capacity of two and a half times the net feed-water required by the engine is the rule given by Rankine.

Proper arrangements for regulating the supply to the boiler are required. Where steam is used for heating purposes the condensed steam is returned to the boiler by the action of gravity, the waste being supplied from time to time by the attendant, through a cock operated by hand.

Feed-water Heaters are devices by which the exhaust-steam from engines is caused to pass through pipes, through which the feed-water also flows in contact with these pipes. A part of the waste heat of the engine is thus utilized in raising the temperature of the feed-water before it reaches the boiler. The saving effected, in units of heat, is the quantity of heat, nearly, required to raise the temperature of the feed-water from its natural temperature to the temperature at which it is supplied to the boiler.

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CHAPTER VII.

BOILER EXPLOSIONS.

257. THE risk of life and property which attends the use of the steam-boiler has always been a source of constant anxiety to the engineer and to the public. Explosions continually take place under circumstances of the utmost apparent security: as they occur without warning and occupy but an instant of time, it is generally impossible, except in rare instances, to ascertain with certainty their true cause, and there is seldom a unanimous opinion on the part of experts who examine into the causes after the event. The loss of life and damage to property often produce great public excitement and private distress, and are sometimes followed by suits for damages or indictments for manslaughter. The question of possible or probable causes has thus, to some extent, assumed a judicial aspect, and it becomes a matter of serious importance not only to ascertain how far explosions may be prevented, but also the degree of individual responsibility to be attached to them.

It has been remarked that the conditions of safety and economy in the case of steam generators, as in nearly all other structures, are in direct antagonism—economy of construction demanding the least amount of costly materials, and safety requiring such an excess of strength as shall place accidents beyond all contingencies of use and management. In the forms of boilers which are most exposed to explosions, it is customary to provide theoretically for a factor of safety of six to eight; that is, an internal pressure of six or eight times the working pressure is supposed to be sufficient to produce rupture.

This theoretical factor is, however, seldom realized. It is doubtful whether boilers of the common forms are ever manufactured so strong that four times the working pressure, if applied, would not cause permanent injury or rupture, and proof-tests of three times the working pressure would be objected to by any manufacturer on the ground that it would permanently injure the structure.

The subject is here introduced and discussed in some of its

aspects, not for the purpose of presenting any special theories or views, but to illustrate some of the applications of the fundamental principles of the dynamic theory of heat to this question. There are evidently numerous possible causes of explosion, some of which may be subjected to exact analysis—and means of preventing such causes may be provided; while there are supposed to be other causes not yet fully understood. In a great majority of cases it is safe to say, however, that explosions arise from defects, or other causes, simple enough in themselves, but which, at the moment, are either hidden from observation or are unavoidable accidents. Excellence in materials and workmanship, and intelligence and watchfulness on the part of the attendant, are the surest guarantees of safety. Where such narrow limits exist, although it may not be possible to state positively all the causes of explosions, yet some of the more evident sources of danger may be pointed out.

It may be asserted, for instance, as a self-evident truth, that the real or remote causes of all explosions may be reduced to two proximate causes. *First*, insufficient strength of the structure to resist the ordinary working pressure. Such a deficiency in strength may arise from an original defect in the materials or workmanship, at the time of construction, or it may be due to deterioration from use, from ordinary wear and tear, or from injuries occurring from mismanagement, want of attention, and repairs, etc. Manufacturers and engineers are supposed to comprehend fully these causes of danger, and it is the object of good engineering and good management to avoid them.

The *second* cause of danger arises from an accumulation of pressure within the boiler, to a dangerous degree, above that which the structure is designed to resist. When the limits of safe *working pressure* are exceeded, the danger begins; and beyond a safe *proof-tension* it becomes imminent.

The accumulation of pressure may be *gradual* and due simply to the increase which accompanies a continued evaporation when there is not sufficient outlet for the steam constantly formed, or it may, according to prevailing ideas, arise from a *sudden* evolution of steam in amounts too great for any ordinary means of efflux; extraordinary stresses being brought to bear from the expansive forces thus generated.

First, in regard to *gradually increasing pressure*, to what

extent may the engineer or stoker be held responsible, or what degree of watchfulness is necessary on his part?

One question to be solved is, at *what rate in time* will the pressure in any given boiler increase if there is a constant rate of ordinary evaporation, and no outlet for the steam? and another, to what extent can the engineer trust the ordinary safety-valve to prevent this gradual increase, or to furnish an outlet for the steam?

The rate of increase of pressure may be found theoretically by means of a formula given by Professor Zeuner in his work on the Mechanical Theory of Heat.

Let τ be the time, in minutes, which must elapse from the instant that all efflux of steam is prevented in a boiler, to the instant when a dangerous or bursting pressure must follow;

Let w represent the weight of water in the boiler;

t_i the temperature of the water due to a dangerous pressure;

t the temperature due to the working pressure;

Q the quantity of heat, in British units, transferred to the water per minute:

Then,

$$\tau = \frac{w (t_i - t)}{Q}$$

will give, with a sufficient degree of approximation, the time in minutes; the mean specific heat of water being taken as unity.

This formula shows that the time will be proportional *directly* to the *amount of water* in the boiler, to the *difference of temperatures* t_i and t , and *inversely* proportional to the quantity Q . The fluctuations of pressure will be less rapid in boilers which contain large quantities of water, and have at the same time a low rate of evaporation. Such conditions are found especially in marine boilers; while the reverse is true for boilers containing small quantities of water, and having rapid rates of evaporation, such as locomotive and fire-engine boilers. The fluctuations will also evidently be more rapid at high pressures than at low pressures, since at high pressures a greater change of pressure occurs with an equal difference of temperatures, than at low pressures.

258. The following examples, as illustrations, will exhibit the applications of the formula:

EXAMPLE I.

A marine tubular boiler of the largest size, such as that exhibited page 136.

$$w = 79,000 \text{ lbs. of water.}$$

Suppose the working pressure to be $2\frac{1}{2}$ atmospheres, and the dangerous pressure to be 4 atmospheres.

The boiler contains 5,000 square feet of heating-surface; and supposing the evaporation to be 3 lbs. of water per hour for each square foot of heating-surface, we shall have, taking as a sufficient approximation in round numbers, 1,000 units of heat as the thermal equivalent of the evaporation of 1 lb. of water.

$$\begin{aligned} t_1 - t &= 29^\circ \text{ F.} \\ q &= \frac{5000 \times 3 \times 1000}{60} \\ \tau &= \frac{79000 \times 29}{\frac{5000 \times 3 \times 1000}{60}} = 9.1 \text{ minutes} \end{aligned}$$

EXAMPLE II.

A locomotive boiler, containing 5,000 lbs. of water, having 11 square feet of grate-surface, and burning 60 lbs. of coal per hour on each square foot of grate. Each pound of coal will evaporate about 7 lbs. of water per hour, making 77 lbs. of water evaporated per minute.

Suppose the working pressure to be 90 lbs. per square inch and the dangerous pressure to be 175 lbs. From the table page 53, we have $t_1 - t = 50^\circ \text{ F.}$

$$\tau = \frac{5000 \times 50}{77 \times 1000} = 3\frac{1}{2} \text{ minutes}$$

EXAMPLE III.

The Steam Fire-Engine.—Taking an actual case. The boiler contains 338 lbs. of water and has 157 square feet of heating-surface. Supposing each square foot of heating-surface to generate only 1 lb. of steam in one hour, the pressure will rise from 100 to 200 lbs. in

$$\tau = 7 \text{ minutes}$$

EXAMPLE IV.

To find, in the same boiler, how long a time will be required to *get up steam*; that is, for instance, to carry the pressure from 0 to 100 lbs. If we suppose only $1\frac{1}{2}$ cubic feet of water to be introduced into the boiler at first, we shall have

$$\tau = \frac{93 \times 117}{157 \times 1000} = 4.1 \text{ minutes}$$

60

The formula shows that if w is diminished by any cause, the time τ is diminished in the same proportion. The lowering of the water in a boiler from failure of the feed-apparatus increases the danger of explosion, therefore, not only by exposing plates to overheating, but by causing a more rapid rise of pressure for the same rate of combustion; while it is not improbable that the rate of evaporation is increased from the same cause, and a further diminution of $\frac{w}{Q}$ thus produced.

These examples, deduced from purely theoretical considerations, have been confirmed by experiments, and serve to indicate the degree of watchfulness required on the part of the engineer.

259. Safety-Valves.—It is supposed that the gradual increase of pressure above discussed can never take place if the safety-valve is in good working order, and if it have proper proportions. Upon this assumption, universally acquiesced in, at least by the public, when there is no other accountable cause, explosions are often attributed to the “sticking” of the safety-valve, “bent valve-stems,” or “inoperative valve-springs.”

As the safety-valve is the sole reliance in case of neglect or inattention of the engine-driver, it is important to examine its mode of working, and the ordinary methods of construction. It should be observed, however, that engineers do not, in practice, place their trust in the safety-valve alone, and that to their watchfulness and attention the public are more indebted for safety than to the apparatus which is designed to regulate the pressure. The skill with which a good engineer will regulate the pressure by checking the evaporation (by opening the fire-doors, or the connection-doors, and by other appliances), is the chief source of safety as far as regards a gradual increase of pressure, and the safety-valve is probably oftener opened

sufficiently by hand, under critical circumstances, than by the action of its own mechanism. It is, however, an indispensable adjunct to a steam generator, and should be made, if possible, such that under its automatic action no considerable increase of pressure above the working pressure will be possible from ordinary evaporation.

The ordinary safety-valve is a disk with a beveled edge, resting on a corresponding seat. The disk is kept down against the boiler-pressure by external pressure variously applied, either by a weight acting with a leverage or by a spring. The opening for the efflux of steam, created by the rise of the valve, is thus an annular opening, the area of which may be approximately found by multiplying the mean circumference of the disk by the rise of the valve measured perpendicularly to the beveled edge. Representing the opening by o , the height of rise by l , and the mean circumference by c , the opening or *orifice* will be approximately

$$o = l \times c$$

The quantity c , or at least the area of the disk of which c is the circumference, is variously estimated in practice, and is in most countries fixed by ordinances; the rules established being based on experiments. One English rule is that the safety-valve *area* shall have half a square inch for each square foot of fire-grate, or, .025 of a square inch for each square foot of heating-surface. Others, quoted by Rankine, are as follows: Let A be the area of the piston, v its velocity in feet per minute, p the excess of pressure in the boiler above that of the atmosphere in lbs. on the square inch, then the area will be

$$a = A \frac{v}{300 p} \text{ nearly}$$

Another quoted by the same author is: " a = area, in square inches = from $\frac{1}{25}$ to $\frac{1}{30}$ of the number of lbs. of coal burned per hour, or a the area in square inches = $\frac{1}{150}$ to $\frac{1}{180}$ of the water evaporated per hour."

The French rule for the diameter of the valve, as given by Peclèt, is

$$D = 2.6 \sqrt{\frac{s}{n - 0.412}}$$

or

$$s' = 5.30 \frac{s}{n - 0.412}$$

in which D is the diameter in centimetres, and s' the area in square centimetres, of the disk, s representing the heating-surface of the boiler in square metres, and n the number of atmospheres of pressure.

The laws of Prussia require that the area of the valve shall be determined by a rule which may be practically stated as follows: p being the absolute internal pressure, the area of the disk in square inches for each square foot of heating-surface

may be found by the formula, $a = \frac{1.2}{p + 15}$. These various for-

mulas give the area of the disk, or pipe closed by the valve—not the *orifice* o , as determined by the equation $\sigma = 1 \times c$.

For the determination, theoretically, of the *orifice* necessary for the efflux into the atmosphere of any given quantity of steam under any given pressure, the velocity of the issuing steam must be ascertained. If we suppose a unit of weight of steam to issue from an orifice with a velocity v , the living force of this

mass will be $\frac{v^2}{2g}$, and this expresses a quantity of work which

is performed by unit of weight of the steam in expanding from the pressure and volume $p_2 v_2$ in the boiler to the pressure $p_1 v_1$ of the atmosphere; for this is the work which actually produces the velocity v . This work for expanding steam, or air, when the heat which is converted into work is drawn from the steam or air itself, can be found when the curve of expansion is known: this curve is called the *adiabatic* curve, a term applied by Mr. Rankine to curves of expansion when no heat is imparted to or abstracted from the expanding gas or vapor. The equa-

tion of such a curve has the form $p v^k = \text{a constant quantity}$, and this equation, first introduced by Poisson, is that from which the laws of the pressures, volumes, and temperatures given on page 33 are obtained, known as Poisson's equations. From these equations the expression for the work of 1 unit of weight of

steam will be $\frac{v^2}{2g} = \frac{k}{k-1} (p_2 v_2 - p_1 v_1)$, from which the value of v can be obtained.

When steam or air issues from a short cylindrical or conoidal opening into the atmosphere, the orifice of the cylinder or cone is not that at which the pressure becomes reduced to the

atmospheric pressure, but that reduction occurs at a point beyond, where the escaping steam spreads out into a conical shape; and hence the area of section in which the pressure p_1 is equal to the atmospheric pressure is greater than the actual *orifice*, or throat of the stream. Supposing the velocity to have been found by the equation just given, the quantity of steam which flows in a second will depend on this effective or greater section of the issuing stream, and also on the *specific volume* of the vapor in this section.

Let w be the weight issuing in a second.

V , the velocity.

r , the section where the pressure is p_1 .

v , the specific volume at the same point.

Then evidently $w = \frac{V}{v} \times r$, an equation from which the section r may be found.

Professor Zeuner gives, in his work on the Mechanical Theory of Heat, the values of V and of w for different absolute pressures in the boiler (the external pressure being constant), from 2 to 14 atmospheres. He states that the values of V thus determined are to be multiplied by a coefficient, which depends partly on the form of the outlet, and partly on the pressures; this coefficient to be determined by experiment. Such experiments were subsequently made by Mr. R. D. Napier, who proposed an empirical formula (given in the Appendix A). The formula of Mr. Rankine, based on the experiments of Napier, also given in the Appendix, for the outflow of steam (stated by him to be a rough practical formula), when the pressure in the boiler is equal to or greater than $\frac{5}{8}$ the external pressure, is

$w = \frac{p_2}{70}$, that is, the weight of steam discharged from an orifice of unit of area *in the throat*, in one second, is one-seventieth of the pressure on the same area in the boiler.

By this rule it becomes easy to find the orifice necessary for the discharge of a given quantity of steam.

The number of pounds discharged per square inch per second being $w = \frac{p_2}{70}$, the quantity for the area A in square

inches will be $A w = \frac{p_2}{70} \times A = W$

$$A = \frac{70 W}{p_2}$$

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EXAMPLE.

260. Suppose a boiler to evaporate 1,800 lbs. of water per hour, what area of orifice (supposed to have the form of a cone of the shape of the contracted vein) will be sufficient for the discharge of all the steam, the pressure in the boiler being 4 atmospheres, or 58.8 lbs. per square inch; we shall have $A =$

$$\frac{70}{58.8} \times \frac{1800}{3600} = \frac{70}{58.8} \times 0.5 = 0.60 \text{ square inches.}$$

The application of the purely theoretical formula of Professor Zeuner, referred to, would give for the orifice under these conditions 0.782 square inches. His ultimate theoretical formula, given in the Appendix, may be applied by taking from the table there given the proper coefficient, under the head of dry-steam, 0.768, giving $0.782 \times 0.768 = 0.60$, the same as above.

This method of finding the orifice is applicable only to orifices of the particular form above mentioned; if it be applied to finding the necessary orifice for safety-valves, it must be assumed that the conditions for an annular orifice, such as that described for the safety-valve, are the same as for the conoidal nozzle.

The orifice of flow in such a case being approximately found by multiplying the *rise* of the valve by the circumference, $o = l \times c$, we shall have

$$l \times c = A = \frac{70}{P_2} \times W, \text{ for all cases in which the internal pressure is equal to or greater than } \frac{5}{8} \text{ of the external pressure.}$$

It is somewhat doubtful whether this assumption in regard to the orifice for common safety-valves can be permitted, but it must be approximately correct for practical purposes.

The quantity l , or rise of the valve, being determined by the resultant of the forces or pressures acting on the upper and lower faces of the disk, has not been theoretically determined; and it is doubtful if it can be so determined. When a safety-valve, as ordinarily constructed, rises from its seat, it is supposed to stand free from its seat all around, and to be supported simply by the pressure of the outflowing steam; but there is no doubt that in all cases lateral pressures act in such a way as to cause the valve to press on one side or the other against its seat, thus giving rise to a small amount of friction.

The pressure underneath the valve after steam commences to flow is always less than the boiler-pressure. For the maximum flow, which occurs for a given orifice when the internal pressure is about $\frac{5}{8}$ of the external pressure, the pressure underneath the valve will bear approximately this ratio to the boiler-pressure; and to maintain a valve in a position away from its seat, the boiler-pressure must always rise above that at which the valve is set. This increase of pressure is at present an unknown quantity, when taken in connection with the action of valves blowing off steam.

The quantity l or rise of valves for given pressures when blowing off, and maintaining the boiler-pressure constant, was determined by Mr. Burg, of Vienna, experimentally, with an ordinary four-inch valve. He found the rise of the valve, in parts of an inch, to be as stated below for the various boiler-pressures given :

For boiler-pressures of

12 20 35 45 50 70 90

the rise of the valve in parts of an inch was

$\frac{1}{36}$ $\frac{1}{48}$ $\frac{1}{54}$ $\frac{1}{65}$ $\frac{1}{86}$ $\frac{1}{168}$ $\frac{1}{168}$

These quantities multiplied by the cosine of the angle of the bevel of the cone will give the values of l , as experimentally determined.

Employing these quantities, we may determine the circumference or diameter d of a valve for the discharge of any given quantity of steam at a given pressure.

EXAMPLE.

Taking the example just given of a boiler which evaporates 1,800 lbs. of water an hour, or 0.5 of a lb. per second, the required area of discharge was found to be, for 4 atmospheres, 0.60 of a square inch.

Taking l , from Burg's experiments, equal to $\frac{1}{80}$ for a pressure of 4 atmospheres, and estimating the diameter to be approximately $\frac{1}{8}$ of c , the circumference, we shall have

$$o = 0.60 = 3 d \frac{1}{80}$$

$$d = 16 \text{ inches}$$

For a given area of disk terminating a cylindrical tube, it is

evident, from geometrical principles, that to obtain an orifice around the edges of the valve equivalent to the *cross-section of the tube*, the valve must rise for conical seats more than $\frac{1}{4}$ of the diameter of the tube.

The above analysis of the action of the ordinary safety-valve is given merely to show the general principles on which this action depends to cause it to serve as an automatic regulator of the pressure; and the results seem to indicate that in practice conical valves are made too small. There would seem to be increased safety at least in making them uniformly larger.

The practical conclusion to be drawn is, that the *ordinary* conical safety-valve, considered as a *regulator of pressure*, is too complicated in its action, and too much influenced by friction and other causes, which cannot be subjected to ordinary rules of construction, to be relied on exclusively as a perfect safety regulator, *i.e.*, as an *automatic means of keeping the boiler-pressure constantly at a given point*. The steam-gauge is in reality the main reliance of the engineer. By the indications of the steam-gauge he can regulate the pressure through other means than the safety-valve, or, if necessary, can raise this valve by hand when it is desirable to keep up at the same time the rate of evaporation.

261. *Sudden Evolution of Steam*.—There are supposed to be, under some circumstances, sudden evolutions of steam in such quantities that no relief is *possible* through the medium of safety-valves, however perfect they may be in their action, and under circumstances in which no warning occurs.

One cause which has received the most general acceptance, both in theory and practice, is the sudden flow of water upon plates which have become overheated by the accidental lowering of the water-level in the boiler. There is no doubt that the exposure of the upper surfaces of flues, or the crown of a furnace, to intense heat, when there is no water upon these surfaces to absorb this heat, is highly injurious and destructive. The weakening of the plates under such circumstances may cause rupture under ordinary pressures. An increase of pressure to a dangerous degree need not *necessarily* follow, however, from such increased evaporation.

Let it be supposed, for instance, that ten square feet of the iron of the flues, $\frac{1}{4}$ of an inch thick, become heated to 1000° F., and water already heated to the boiling-point due to the pressure,

say 300° F., to flow over these plates; the cooling of the plates from 1000° to 300° F. will cause a transfer of heat to the water of

$$Q = w \times c' \times (t_1 - t) \text{ units of heat}$$

or $Q = 100 \text{ lbs.} \times 1138 \times 700 = 7900 \text{ units}$

sufficient to evaporate only about 7.9 lbs. of water.

If the circulation of the water is such that this quantity of heat is equally diffused, the quantity of heat evolved would not elevate the pressure to a dangerous degree in the case given, under ordinary circumstances.

The effect of overheated plates in superheating steam already formed may be found thus: Let w be the weight of steam, c' its specific heat at constant volume = .475; then,

$$Q = w c' (t_1 - t)$$

and

$$p_1 v = R T_1$$

$$p v = R T$$

p_1 being the dangerous pressure, p the working pressure, t_1 and t being the corresponding temperatures, and v the specific volume, supposed constant.

From these equations we get

$$t_1 - t = T_1 - T = \frac{v(p_1 - p)}{R} = \frac{v(p_1 - p)}{83.422}$$

in which the steam is supposed to be *dry* saturated steam.

The quantity Q may then be found.

The evolution of steam from overheating of plates, or the action of such plates in superheating steam, although comparatively sudden, would not necessarily be so sudden as to prevent relief through a perfectly efficient safety-valve. The process of transfer of heat in these cases must, to a certain extent, be gradual, and time would be allowed for the efflux of the steam under most circumstances.

A *sudden evolution* of steam beneath the water-level of a boiler, arising from any cause, such as the "spheroidal condition," or concussive "ebullition," is another supposed danger. In this case it has been suggested that the impact of a mass of water thrown against opposite plates may cause rupture; though a more rational theory seems to be that the injury in such cases would arise from the violent reaction instead of from direct impact. The plates and joints of a boiler being already stretched to their extreme limit of elasticity, the reaction of a sudden expansion

of steam beneath the water-level might be transmitted by hydrostatic pressure over a large area, and have the same effect as the explosion of a charge of gunpowder upon a submerged rock.

The whole subject of sudden evolutions of steam requires, perhaps, more than any other, careful and proper experiments to determine the character and extent of the danger which may arise from this cause, or whether it occurs at all. Free and continued circulation of water, *even if it be accomplished by a forced operation*, would probably be advantageous in diminishing the liability to sudden evolutions of steam, while it would at the same time *increase the efficiency of the heating-surfaces* at a comparatively small cost.

APPENDIX A.

THE law known as Mariotte's law, and also as Boyle's law (discovered by Mariotte in 1740), is a simple law in regard to perfect gases, determined by experiment, which may be enunciated as follows: "The temperature of the gas remaining constant, the volumes of the same weight at different pressures will be inversely as the pressures." Thus $p v = p' v'$ or $\frac{p}{p'} = \frac{v'}{v}$.

If densities be considered, the volumes being inversely as the densities, the law may be stated in other words; thus, "at the same temperature, the densities of a given quantity of a perfect gas occupying different volumes will be proportional to the pressures. Thus $p \frac{1}{D} = p' \frac{1}{D'}$ or $\frac{p}{p'} = \frac{D}{D'}$.

The experiments of Gay-Lussac on the expansion of gases, with constant pressure, led him to the discovery that "the augmentation of volume which a perfect gas receives when the temperature is increased 1° , is a fixed proportion of its initial volume at the temperature of melting ice; or $v' = v_0 (1 + a t)$, in which (a) is a coefficient of expansion, nearly the same for all perfect gases. Combining this discovery with the law of Mariotte, the relation $\frac{v}{v_0} = \frac{p_0}{p} \left(\frac{1 + a t}{1 + a t_0} \right)$, known as the law of *Mariotte and Gay-Lussac*, is determined. From this relation is easily derived the general form $p v = R (a + t)$ or $p v = R T$, which occurs in the text (see page 25).

Poisson discovered that when, during the expansion or compression of a gas, no heat is transmitted to, or abstracted from, the gas (the cooling or heating due to the work involved being thus confined to the gas itself), the law which expresses the relation between the pressure and volume will take the form, algebraically,

$$p v^k = p_1 v_1^k = \text{a constant.}$$

From this equation we have directly

$$\frac{p v}{p_1 v_1} = \left(\frac{v_1}{v} \right)^{k-1}$$

or since $p v = R T$ and $p_1 v_1 = R T_1$

$$\frac{T}{T_1} = \left(\frac{v_1}{v} \right)^{k-1}$$

and the other equations of page 33 are found in the same manner.

The equation $p v = R T$, when T is constant, is the equation of an equilateral hyperbola, which is the curve of expansion of a perfect gas when the temperature is kept constant by a supply of heat to the gas equivalent to the work of expansion. The equation $p v^k = p_1 v_1^k = \text{constant}$ is the equation of a curve of expansion, called the *adiabatic* curve, which is the curve representing the relations of the pressure and volume when a gas expands against a pressure, the heat which is converted into work being drawn from the gas itself. The expression for the work performed under such conditions is given page 33 in terms of the initial and final volumes. A corresponding expression for the work in terms of the initial and final pressures, is—

$$w = \frac{1}{k-1} p_1 v_1 \left[1 - \left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} \right]$$

The value of k for wet steam is 1.105 (0.7 by weight being steam, and 0.3 water). For dry steam $k = 1.135$, for superheated steam $k = 1.333$, and for air $k = 1.41$.

APPENDIX B.

THE following are Professor Zeuner's formulæ for the flow of vapors and gases from orifices, to which tables of coefficients have been added, calculated from these formulæ for convenience of calculation.

On page 157 and on page 402 of Professor Zeuner's work on the Dynamic Theory of Heat, French edition, we have the equation—

$$(1) \quad \frac{w^2}{2g} = - \int v \, dp$$

w representing the velocity of efflux; v the specific volume; and p the pressure. Assuming that the form of the adiabatic curve for vapors is the same as for gases, viz.: $p v^k = \text{constant}$, (2) we can, by finding the value of v in equation (2) and substituting in equation (1), get

$$(3) \quad w = \sqrt{2g \frac{k}{k-1} (p_2 v_2 - p_1 v_1)}$$

a formula first deduced by Weisbach, which is true for any gas or vapor that has for the equation of its adiabatic the form $p v^k = \text{constant}$. The different values of k for steam in different conditions, and for air, are given on the preceding page.

Equation (3) is also identical with equation (337), page 406 (Zeuner), from which he calculated the values of w on page 409.

Equation (3) is best adapted for discussion, and will therefore be employed instead of (337).

Equation (3) can be changed into the following forms:

$$(4) \quad w = \sqrt{2g \frac{k}{k-1} p_2 v_2 \left[1 - \left(\frac{p_1}{p_2} \right)^{\frac{k-1}{k}} \right]}$$

$$(5) \quad w = \sqrt{2g \frac{k}{k-1} p_1 v_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{k-1}{k}} - 1 \right]}$$

From equation (331), page 403 (Zeuner), we get

$$(6) \quad \frac{G}{F} = \frac{w}{v_1}$$

Substituting in (6) eq. 3 and 4, and remembering that $p_2 v_2^k = p_1 v_1^k$
 $v_1 = \left(\frac{p_2}{p_1}\right)^{\frac{1}{k}}$, we get equations (7) and (8).

$$(7) \quad \frac{G}{F_1} = \sqrt{2g \frac{k}{k-1} \frac{p_1}{v_1} \left[\left(\frac{p_2}{p_1}\right)^{\frac{k-1}{k}} \right]}$$

$$(8) \quad \frac{G}{F_1} = \sqrt{2g \frac{k}{k-1} \frac{p_2}{v_2} \left[\left(\frac{p_1}{p_2}\right)^{\frac{2}{k}} - \left(\frac{p_1}{p_2}\right)^{\frac{k-1}{k}} \right]}$$

Equations 4, 5, 7, and 8 are theoretical equations in which friction is neglected, and in which F represents that section of the stream in which there exists the external pressure p_1 , and hence F_1 may be variable. The section just mentioned is called by Professor Zeuner the *efflux section* to distinguish it from the *orifice section*. Rankine calls it the *effective area*.

G is supposed to be known and constant.

Equation (3) was deduced by supposing that while the fluid is expanding from the boiler into the external space, heat is neither furnished nor abstracted; but this is not exactly the case in practice, because the fluid on its way to and at the orifice gives rise to *friction*, which in turn produces heat; so that, strictly speaking, heat is furnished to the fluid in an amount almost equivalent to the friction (an insignificant quantity of heat being lost by conduction). So that the true curve of expansion is not the adiabatic curve, but one which will take a position above the latter, and which Zeuner shows for gas to have the form $(p v^n = \text{const.})$ (9) in which

$$(10) \quad n = \frac{(1+z)k}{1+zk}$$

This n Professor Zeuner calls the *coefficient of efflux*. Its value evidently depends on z and k . z is a coefficient of resistance, and is equal to the ratio of the actual (not theoretical) living force to the resistances of the issuing fluid, *i.e.*, arising from friction and oscillations.

$$z = \frac{\text{Friction}}{\text{Actual Living Force}}$$

It is only apparently like Weisbach's coefficient, and is to be determined by experiment.

k is the exponent in the equation of the adiabatic curve. By combining

equations 9, 6, and 3 in the same way as 6, 3, and 2, we get equations similar to 8, 7, 5, and 4.

$$(11) \quad w = \sqrt{2g \frac{k}{k-1} p_2 v_2 \left[1 - \left(\frac{p_1}{p_2} \right)^{\frac{n-1}{n}} \right]}$$

$$(12) \quad w = \sqrt{2g \left(\frac{k}{k-1} \right) p_1 v_1 \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]}$$

$$(13) \quad \frac{G}{F_1} = \sqrt{2g \frac{k}{k-1} \frac{p_1}{v_1} \left[\left(\frac{p_2}{p_1} \right)^{\frac{n-1}{n}} - 1 \right]}$$

$$(14) \quad \frac{G}{F_1} = \sqrt{2g \frac{k}{k-1} \frac{p_2}{v_2} \left[\left(\frac{p_1}{p_2} \right)^{\frac{2}{n}} - \left(\frac{p_1}{p_2} \right)^{\frac{n+1}{n}} \right]}$$

Equations 4, 5, 11, and 12 give the velocity of the particles in feet or metres per second. Equations 7, 8, 13, and 14 give the quantity of fluid which flows through unit of area, in pounds or kilograms, per second. This last Rankine calls *mass velocity*. In equations 13 and 14 it must be remembered that F_1 still represents the *efflux section* of the stream, and p_1 the pressure in that section.

It can easily be shown by analyzing equations 4, 5, 11, and 12 that both when there is friction and when there is no friction, the velocity w in the *efflux section* never attains a maximum, but depends entirely on the difference of pressures in the boiler and in the external space.

Equations 8 and 14, however, show that there is a maximum *mass velocity* when

$$(15) \quad \frac{p_1}{p_2} = \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}} \text{ (theoretically), and}$$

$$(16) \quad \frac{p_1}{p_2} = \left(\frac{2}{n+1} \right)^{\frac{n}{n-1}} \text{ (actual)}$$

Napier's experiments go to show that when there is a *constant inside pressure* and a *variable outside pressure*, there is a certain ratio between these two pressures when both the velocity w and the $\frac{w}{v}$ in the *plane of the actual orifice* attain a maximum. His experiments also show that if the external pressure (not that in the actual orifice) falls below that value

which gives a maximum, the pressure in the plane of the actual orifice will remain constant, even if the external pressure should become 0. When

$$\frac{p_1}{p_2} = \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \text{ or } > \text{ greater than } \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

the pressure in the plane of the orifice is equal to the external pressure. But when

$$\frac{p_1}{p_2} \text{ is less than } \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

the pressure p in the plane of the actual orifice is given by the equation

$$(18) \quad p = p_2 \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

Independent, therefore, of the external pressure, experiment and theory both seem to show that when there is a constant inside pressure and a variable external pressure, the pressure in the *plane of the orifice* can never fall below the value given in equation 18, *i.e.*, the value corresponding to a maximum efflux. It may go above that value, but never below.

If it be desired to find an orifice that will discharge a given weight G in a unit of time, the pressure in the reservoir being constant, and equal to p_2 , and the external pressure in the receiver being p_1 , the process will be as follows:

First, find the pressure in the plane of the actual orifice; this will be the same as the actual pressure p_1 if p_1 is equal to, or greater than,

$p_2 \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$. But if p_1 is less than this quantity, then the pressure p in the plane of the orifice will be

$$p = p_2 \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$$

Then substitute one or the other of these values in equation (14), and regard F_1 as being the actual orifice, which may then be called F . n can be obtained from equation (10) or from the following tables.

Rankine gives the following rough formulæ for finding the efflux of steam, which are intended to be sufficiently accurate for practical purposes:

In the first case, when $p_2 =$ or greater than $\frac{5}{3} p_1$, then,

$$\frac{G}{F} = \frac{p_2}{70}$$

p_1 and p_2 being absolute pressures.

In the second case, when p_2 is less than $\frac{5}{3} p_1$,

$$\frac{G}{F} = \frac{p_1}{42} \sqrt{\frac{3}{2} \frac{p_2 - p_1}{p_2}}$$

Napier's formulæ are—

First, when p_2 is greater than $2 p_1$,

$$\frac{G}{F} = 210 \sqrt{\frac{p_2}{v_2}}$$

Second, when p_2 is less than $2 p_1$

$$\frac{G}{F} = 420 \sqrt{\frac{p_1}{p_2} \left(1 - \frac{p_1}{p_2}\right) \frac{p_2}{v_2}}$$

In these formulæ F represents the actual orifice, and G the weight of steam discharged per second.

When p_1 is less than $p_2 \left(\frac{2}{n+1}\right)^{\frac{n}{n-1}}$ (which is true for steam in all cases in which p_2 is greater than $1.726 p_1$), then the pressure p in the plane of the orifice becomes $p = p_2 \left(\frac{n}{n+1}\right)^{\frac{n}{n-1}}$, and this introduced into equation 14 gives

$$\frac{G}{F} = \left(\frac{2}{n+1}\right)^{\frac{1}{n-1}} \sqrt{2g \frac{k}{k-1} \left(\frac{n-1}{n+1}\right) \frac{p_2}{v_2}}$$

Supposing the resistances constant, this is equivalent to

$$\frac{G}{F} = C \sqrt{\frac{p_2}{v_2}}$$

a form corresponding to that found by Napier from experiment.

TABLE I.*

Showing the ratio of the actual orifice to the theoretical orifice $\frac{F}{F_1}$ in the efflux of wet and dry steam, the value of F being found from equations 7 and 8, friction being neglected; the value of F_1 being found from equations 13 and 14, friction being taken into account.

Absol. press. in atmos.	Wet Steam.				Dry Steam.			
	z = 0.065	z = 0.100	z = 0.505	z = 0.9601	z = 0.065	z = 0.100	z = 0.505	z = 0.9601
1.25					1.03171	1.0449	1.2360	1.4119
1.50					1.0333	1.0504	1.2421	1.4207
1.714	1.0344	1.0522	1.2420	1.4279				
1.732					1.0357	1.0542	1.2474	1.4393
1.856								
1.900								
2.000	1.0169	1.0344	1.2211	1.4038	1.0203	1.0385	1.22903	1.4179
4.00	0.7535	0.76835	0.90699	1.0428	0.76792	0.78164	0.92427	1.06710
7.00	0.53262	0.54054	0.63953	0.72686	0.54678	0.55655	0.64166	0.75983
10.000	0.41593	0.42309	0.49943	0.57419	0.4363	0.43771	0.50465	0.59759
14.000	0.32588	0.33149	0.39130	0.44987	0.33867	0.34432	0.39697	0.46464
k	1.105	1.105	1.105	1.105	1.135	1.135	1.135	1.135
n	1.098	1.0946	1.0675	1.0509	1.1257	1.1212	1.0858	1.0646

In the wet steam, 0.7 by weight is supposed to be steam and 0.3 water. $k = 1.105$ is the exponent of the adiabatic curve of the fluid, z is a coefficient of resistance due to friction = the ratio of friction to actual living force = $\frac{\text{Friction}}{\text{Actual Living Force}}$ of the issuing fluid. $n = \frac{(1 + z) k}{1 + z k}$, and hence less than k .

TABLE II.*

Showing the ratio of the actual orifice of discharge to the theoretical $\frac{F}{F_1}$ in the efflux of superheated steam and air; the value of F being found by equations 7 and 8, friction being neglected; F_1 being found from equations 13 and 14, friction being taken into account.

Absol. press. in atmos.	Superheated Steam.				Air.			
	z = 0.065	z = 0.100	z = 0.505	z = 0.9601	z = 0.065	z = 9.100	z = 0.505	z = 0.9601
1.856	1.0393	1.0599	1.27375	1.4194				
1.900					1.0423	1.0624	1.2832	1.5014
2.000	1.0355	1.0561	1.2691	1.4144	1.0414	1.0615	1.2821	1.4949
4.000	0.83547	0.85206	1.02400	1.14110	0.85885	0.87539	1.0573	1.2370
7.000	0.62975	0.64211	0.77180	0.86093	0.65914	0.67183	0.8114	0.9494
10.000	0.51369	0.52287	0.62960	0.70155	0.54397	0.55445	0.66967	0.78354
14.000	0.41929	0.42761	0.51390	0.57265	0.44899	0.45763	0.55273	0.6467
k	1.3333	1.3333	1.333	1.333	1.41	1.41	1.41	1.41
n	1.30675	1.2941	1.1992	1.1460	1.3754	1.3593	1.2395	1.174

* Calculated from the foregoing formulæ, by Mr. J. F. Klein.

In the wet steam, 0.7 by weight is supposed to be steam, and 0.3 water. $k = 1.105$ is the exponent of the adiabatic curve of the fluid $p v^k = \text{const.}$ z is a coefficient of resistance equal to the ratio of friction to the actual (not theoretical) living force of the issuing fluid. When friction is taken into account the adiabatic curve changes to the curve represented by $p v^n = \text{const.}$ in which $n = \frac{(1 + z)k}{1 + zk}$ and hence less than k .

According to a principle of hydraulics, z is assumed by Professor Zeuner to be constant for the same kind of tube and orifice of discharge, however the diameter of orifice, or the pressure, may vary. This is allowable when the tubes which form the orifice are rounded on the inner edges.

From equation (3) or an identical equation Prof. Zeuner has calculated (*Théorie de la Chaleur*) the velocities of steam issuing from an orifice in a boiler, and from these the quantity of flow per unit of effective or theoretical area, for different absolute pressures. The velocities are as given below:

Internal absolute pressures. Atmospheres.	Velocities in metres per second.	Flow of steam per second, in pounds, per square inch of section.
1 .....	.....	.....
2	481.72	0.434
3	606.62	0.559
4	681.56	0.639
5	734.42	0.698
6	775.00	0.744
7	807.82	0.783
8	835.00	0.815
9	858.41	0.845
10	878.92	0.869
11	896.87	0.892
12	913.05	0.911

To use this table, let it be required to find an orifice which will discharge a given weight, w , of dry steam per second at a given pressure; for instance, the orifice that will discharge 1,800 pounds per hour, or 0.5 pounds per second, at four atmospheres.

In the third column we find the weight discharged per square inch per second, viz.: 0.639 pounds, then $\frac{w}{.639} = A$, the theoretical orifice, or ori-

fice in the effective section; $\frac{w}{0.639} = \frac{.5}{.639} = .783$. Then find the proper coefficient for 4 atmospheres from the tables, viz.: .768, and $.783 \times .768 = 0.60$ square inch. For superheated steam and air the process is similar after finding the flow per square inch per second from the theoretical formula.



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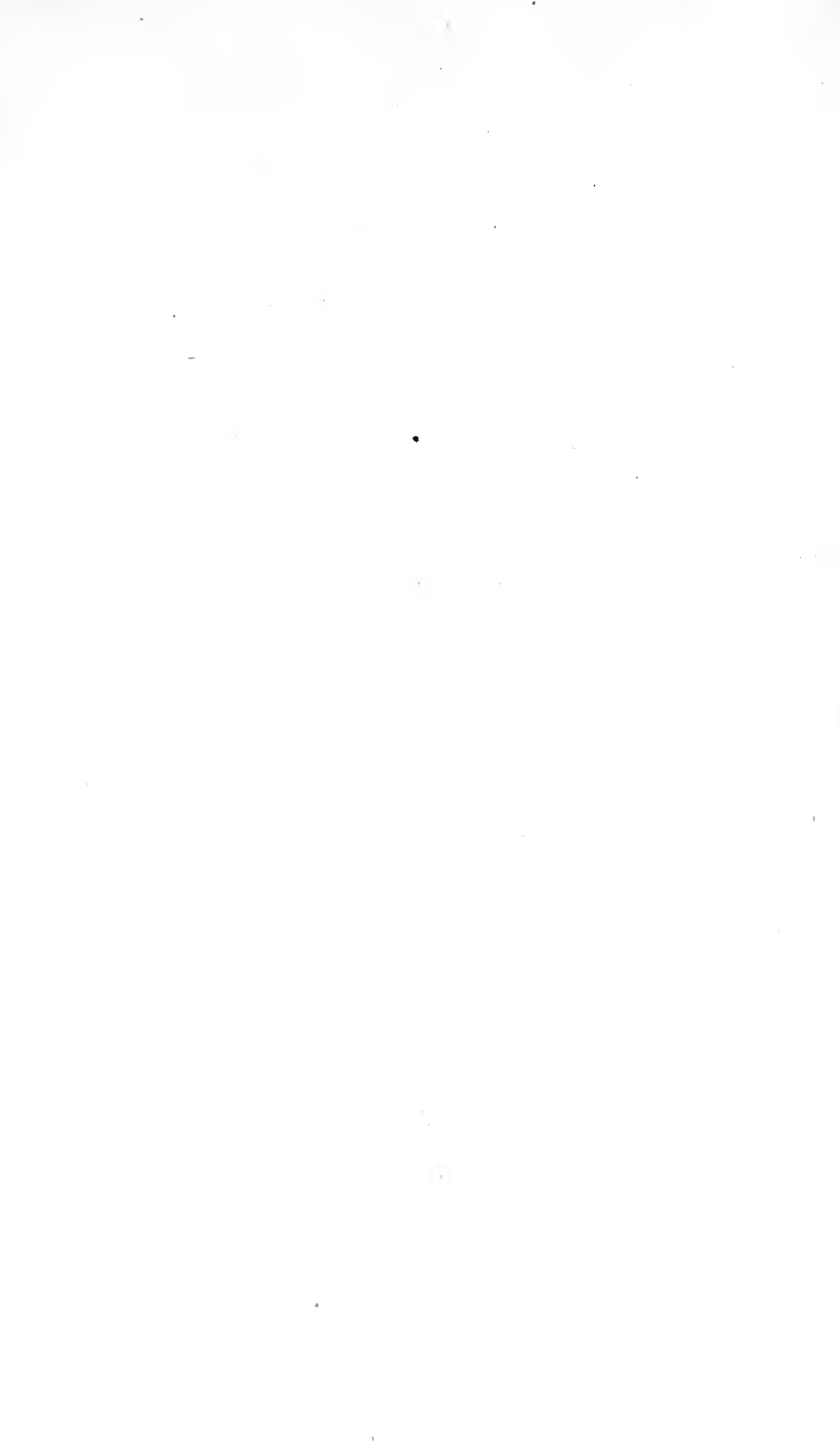
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